2D SPH SIMULATIONS OF A SINGLE PLANET MIGRATION IN A PROTOPLANETARY DISC

Vincenzo Costa (1)

Valerio Pirronello (1)

Gaetano Belvedere (2)

Antonino Del Popolo (2)

Diego Molteni (3)

Giuseppe Lanzafame (4)

(1): Dipartimento di Metodologie Fisiche e Chimiche per l'Ingegneria - Università di Catania - Viale A. Doria 6, 95126 Catania

(2): Dipartimento di Fisica e Astronomia dell'Università - Sezione Astrofisica - Via S. Sofia 78, 95123 Catania

(3): Dipartimento di Fisica e Tecnologie Relative - Università di Palermo - Viale delle Scienze 90128 Palermo

(4): INAF - Osservatorio Astrofisico di Catanie - Via S. Sofia 78, 95123 Catania

Exoplanets

Nearly 300 Extra-Solar planets detected

Masses in the range ~ 10 M_{earth} - 10 $M_{jupiter}$

- Laughlin G., http://www.scholarpedia.org/article/Exoplanets
- http://exoplanets.eu
- http://exoplanets.org
- Butler et al. 2006, ApJ 646, 505

Possible formation process within an accretion disc

1) grain coalescence in kilometre-sized planetesimals;
2) growing-up to 100 Km planetesimals;
3) "oligarchic" growing-up of protoplanets by collisions with other minor objects, over 10 terrestrial masses beyond 3 AU, or the formation of martian and earth-like planets within 3 AU.

Disk planet interaction

1) Lindblad resonances in the accretion disc (Goldreich & Tremaine 1980)

2) gravitational torques on the planet's orbit, causing planet migration

3) formation of a density gap in the region of a planet's orbit, depending on planet's mass

4) two main migration mechanism: (Ward 1997)

   - type I --> planet embedded in the disc (gravitational torque)

   - type II --> planet centred in the disc gap (viscosity)

5) migration times of the order of 10^4-10^5 years, starting from about 5 AU are currently predicted (Nelson & Papaloizou 2004)

6) observational discovery of many Jupiter-like planets below 3 AU

Disk planet interaction modelling

Most common assumptions (review by Artymouicz 2004)

- Keplerian distribution of velocities
- laminar fluid motion

Grid based numerical schemes

The SPH (Smoothed Particle Hydrodynamics) Method

Lagrangian method based on smoothing “particles”

$$A_i = \sum_{j=1}^{N} m_j \frac{A_j}{\rho_j} W(\boldsymbol{r_i} - \boldsymbol{r_j}, h)$$

$$\int W(\boldsymbol{r} - \boldsymbol{r}', h)\, d\boldsymbol{r}' = 1$$

$$\lim_{h \to 0} W(\boldsymbol{r} - \boldsymbol{r}', h) = \delta(\boldsymbol{r} - \boldsymbol{r}')$$

h --> smoothing length → spatial resolution

- momentum equation
- energy equation
- gas

$$\frac{d\boldsymbol{v}_i}{dt} = -\sum_j m_j \left(\frac{P_j}{\rho_j^2} + \frac{P_i}{\rho_i^2} + \pi_{ij} \right) \nabla_i W_{ij} + \boldsymbol{g_i}$$

$$\frac{du_i}{dt} = \frac{1}{2} \sum_j m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} \right) (\boldsymbol{v_i} - \boldsymbol{v_j}) \cdot \nabla_i W_{ij}$$

$$P = (\gamma - 1) \rho u$$

Models

- 2D
- dimensionless code, reference quantities:

  1) initial stellar mass M_0 (star mass appears as 1 at the beginning)

  2) stellar radius R_0

  3) keplerian orbital period of an orbit of radius R_0 around a star of mass M_0

$$T_0 = 2\pi\sqrt{\frac{R_0^3}{G M_o}}$$

- Planet can capture particles
- No self gravitation of the disc
- Planet pseudo-atmosphere through an associated SPH planet-particle
- 2 sets of models: Keplerian (gas velocity distribution)

  sub-Keplerian

Sub-keplerian Models

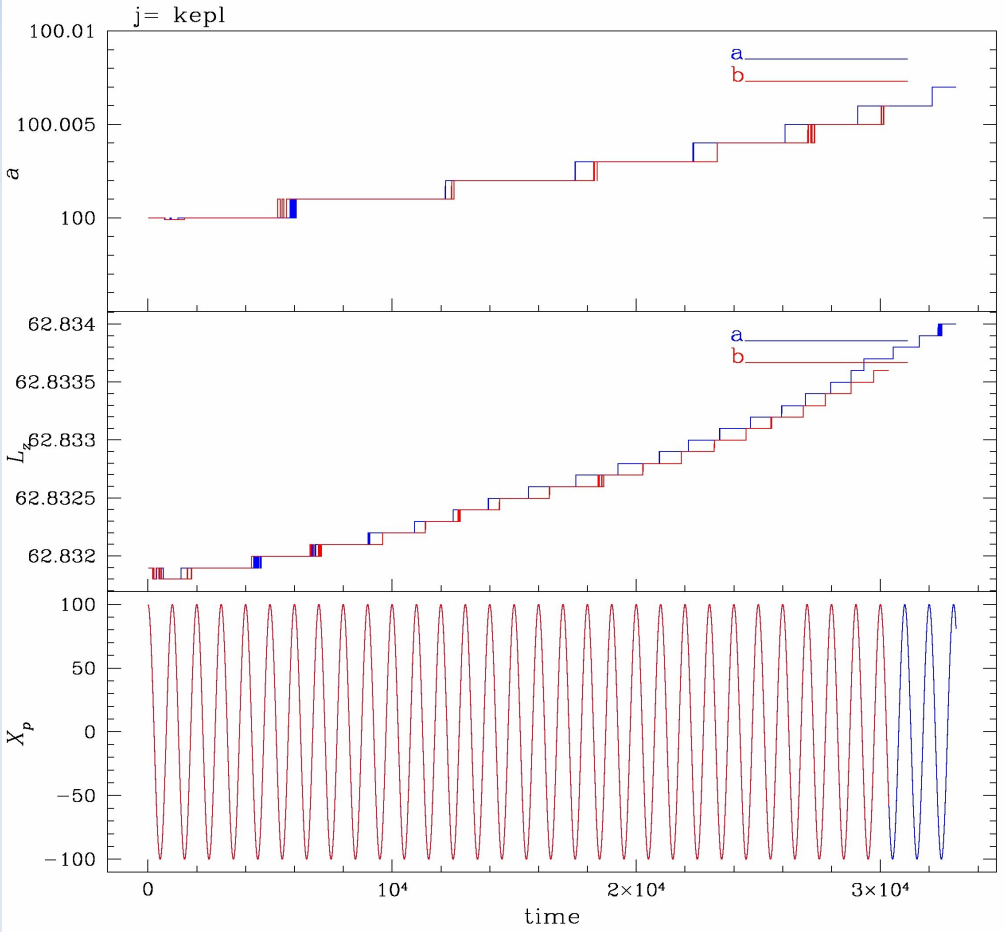
- Initial planet masses 10^{-7} 10^{-3}
- Particles injected at a distance of 130
- Angular momentum (per unit mass)

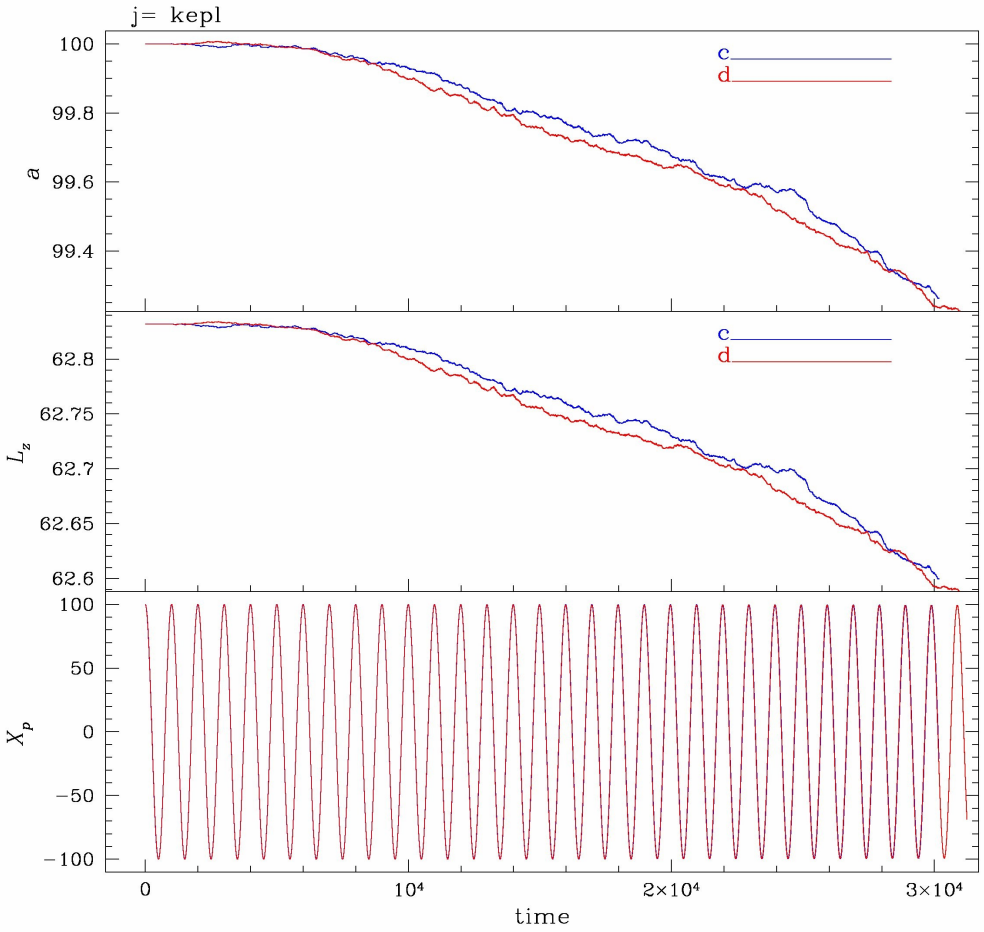
  18 36 54 (~70 is keplerian)
- Particle masses 10^{-11}
- "Steady" state accumulation of particles with $N_p \sim 10^5 - 10^6$ with $h = 0.3$
- Initial planet eccentricity ~ 0
- Initial orbit dimension ~ 100 (1 AU for $M_0 = M_{sun}$)

Orbital parameters evolution (Keplerian)

(Costa et al. 2009, submitted)

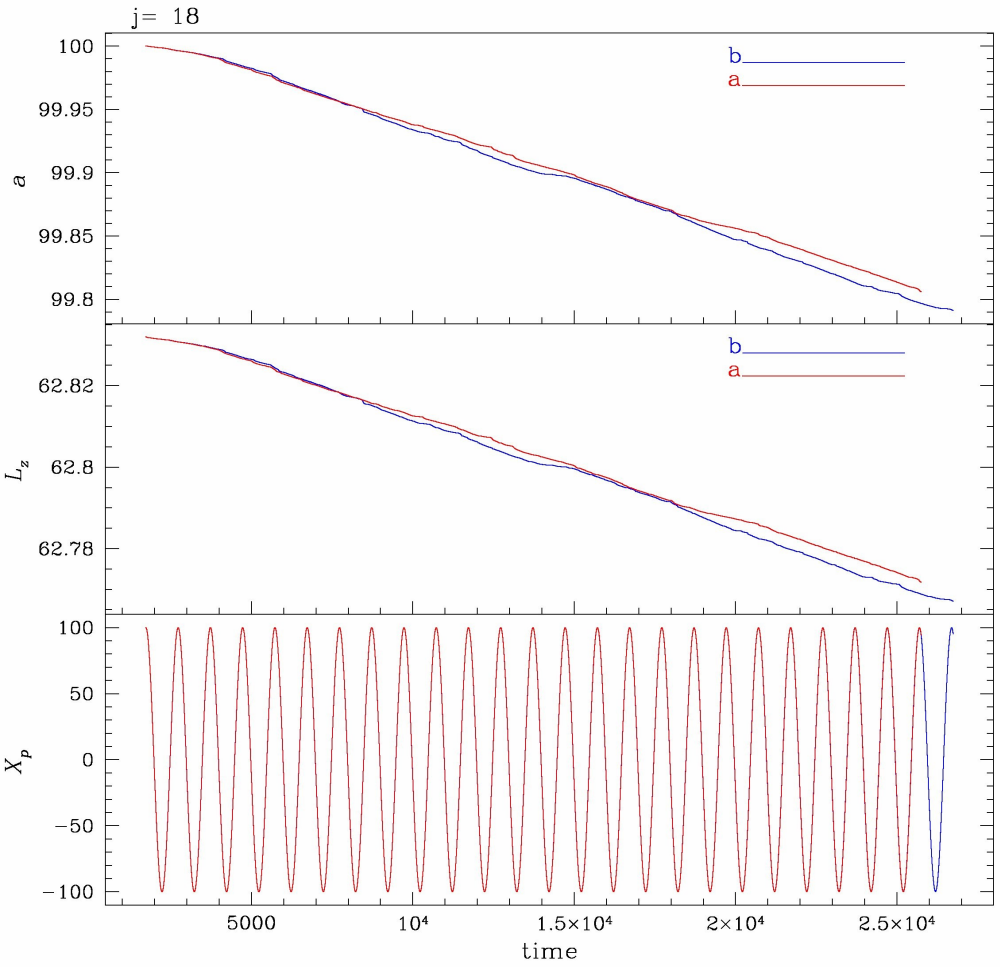
Model	Planet mass	pseudo-atmosphere
a	Jovian	no
b	Jovian	yes
c	Earth	no
d	Earth	yes

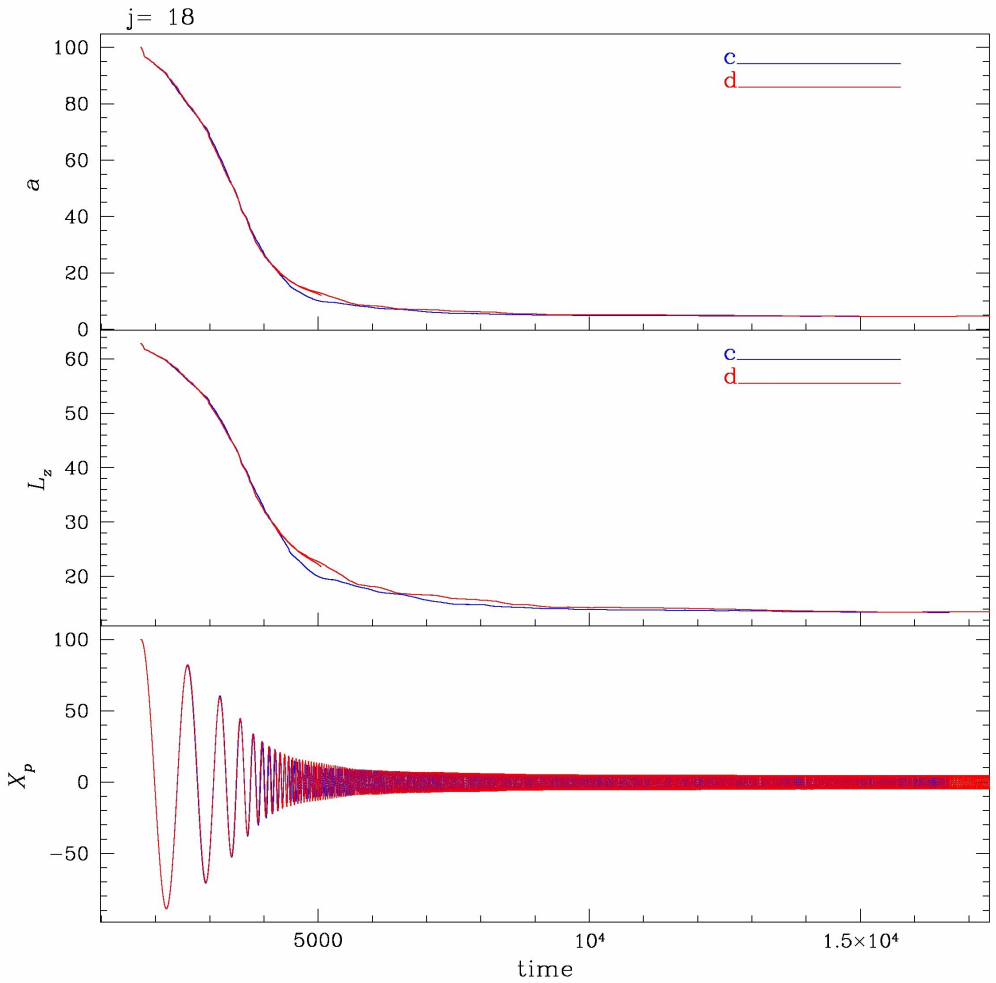




Orbital parameters evolution (sub-Keplerian j=18)

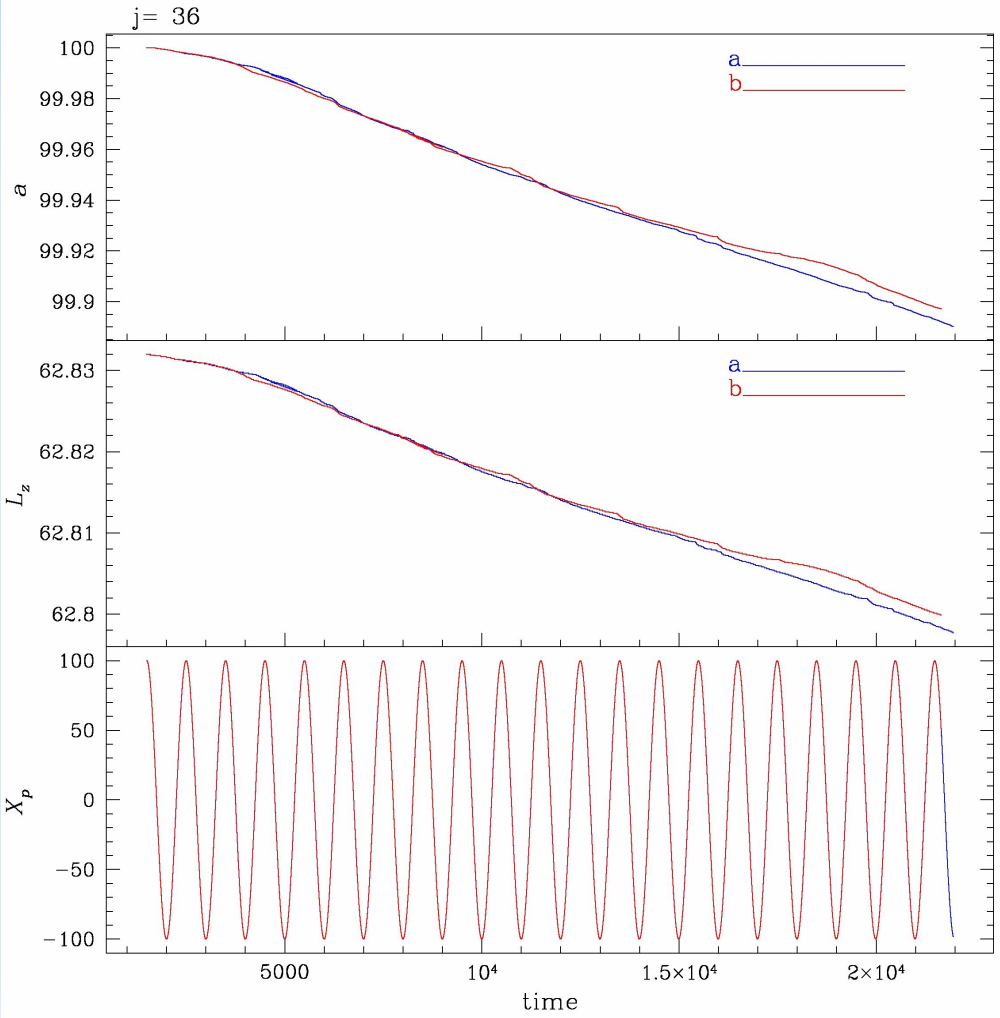
Model	Planet mass	pseudo-atmosphere
b	Jovian	no
a	Jovian	yes
c	Earth	no
d	Earth	yes

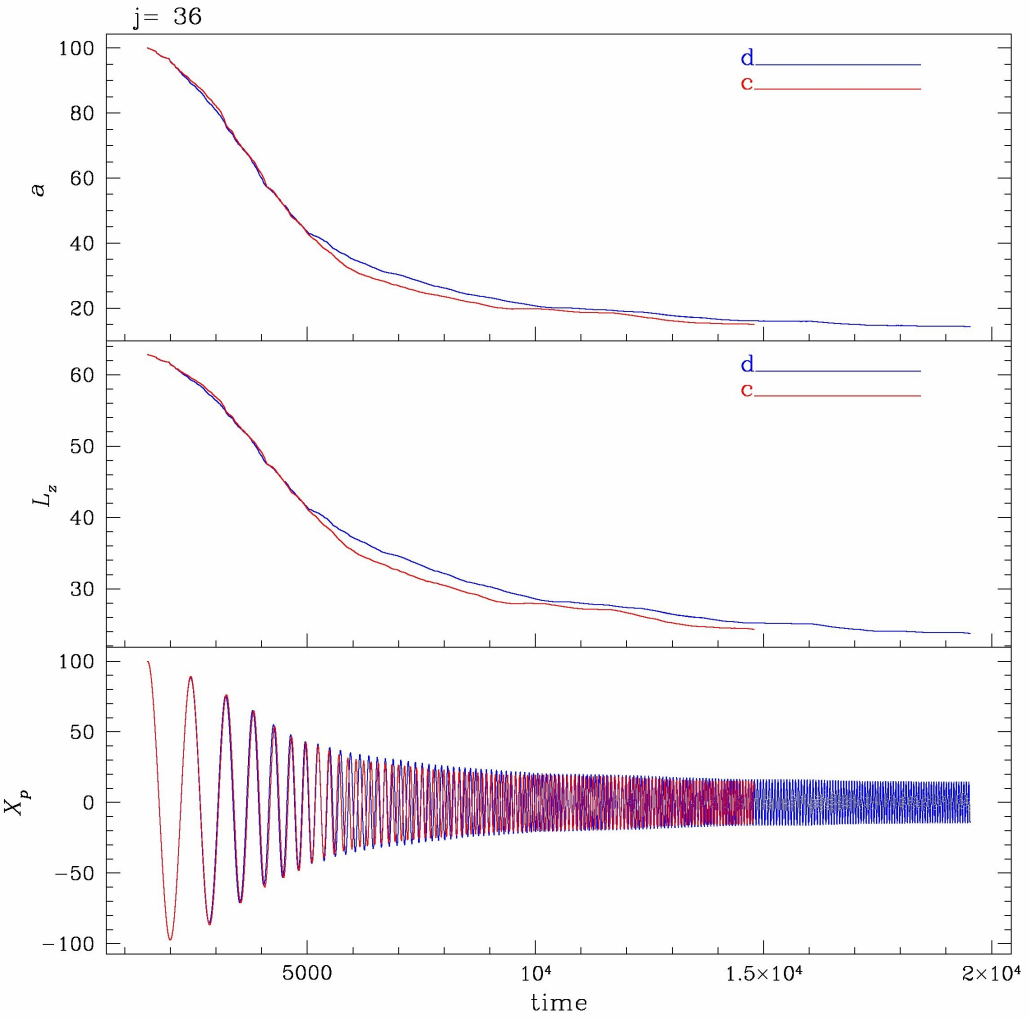




Orbital parameters evolution (sub-Keplerian j=36)

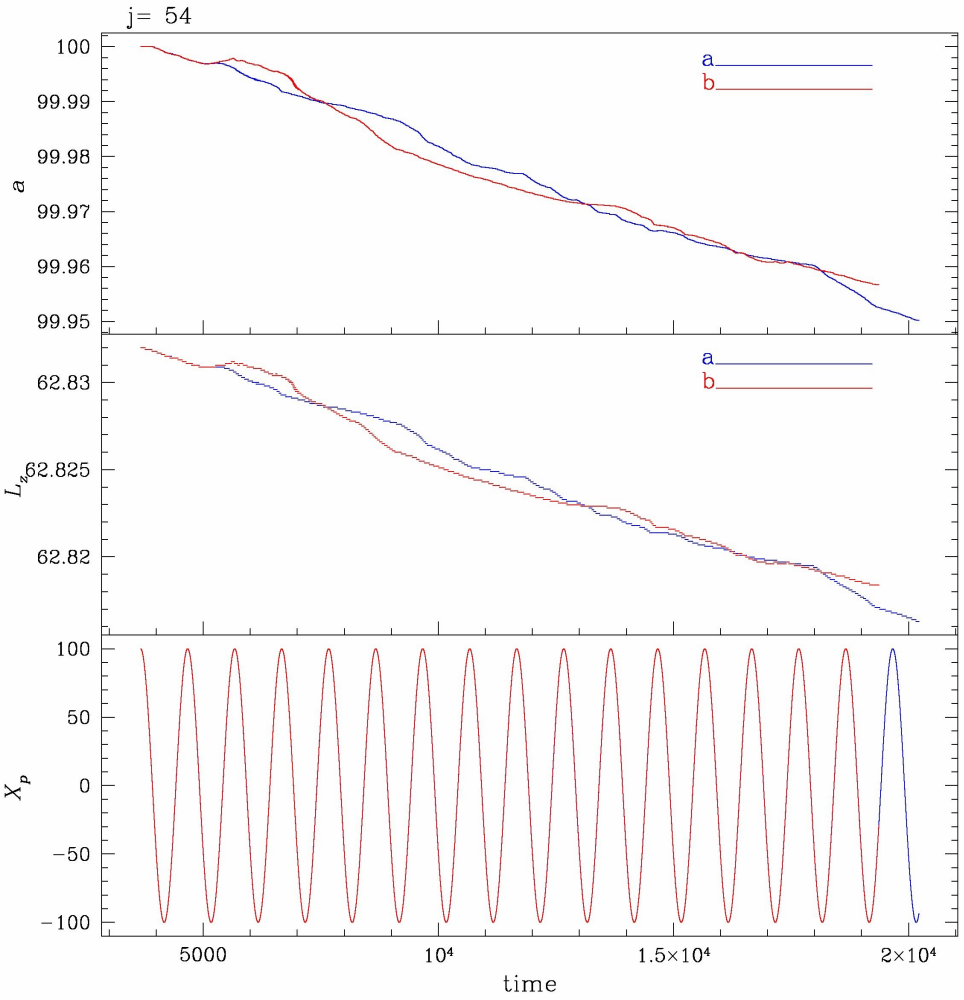
Model	Planet mass	pseudo-atmosphere
a	Jovian	no
b	Jovian	yes
c	Earth	no
d	Earth	yes

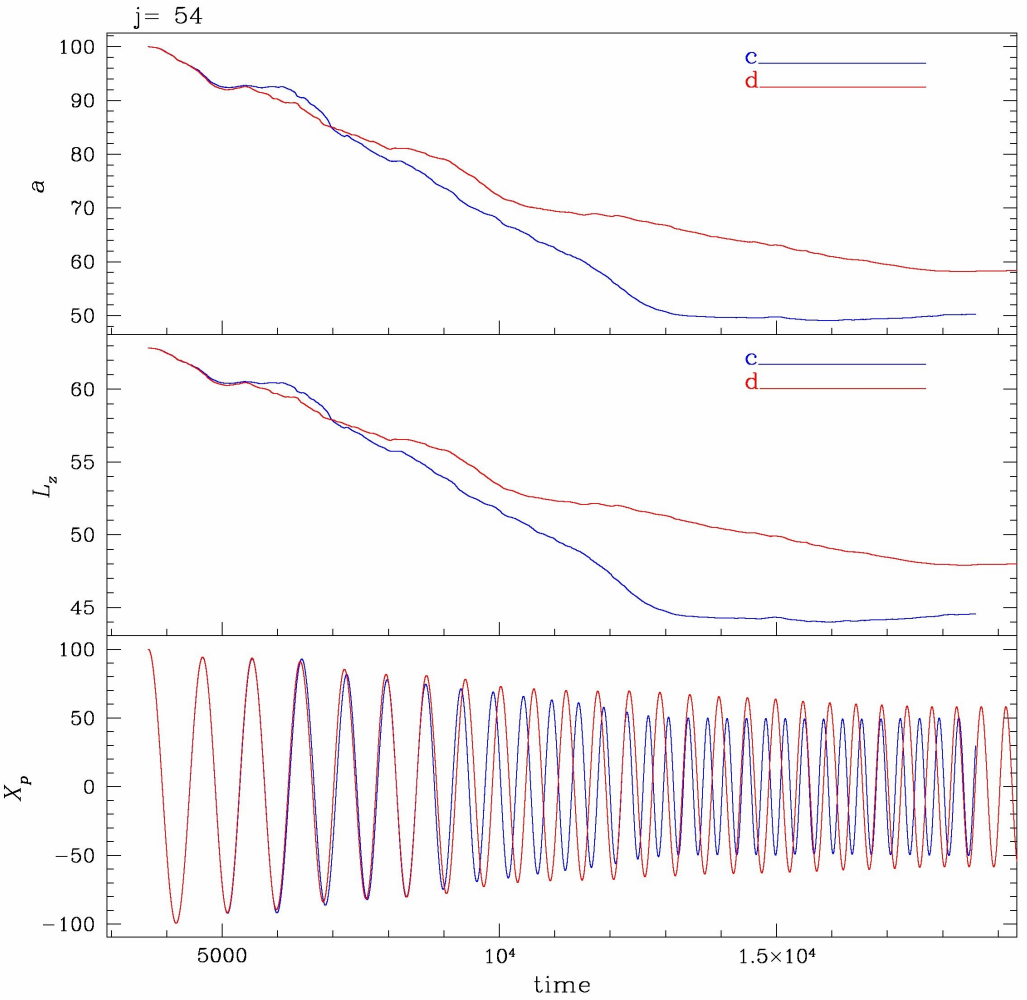




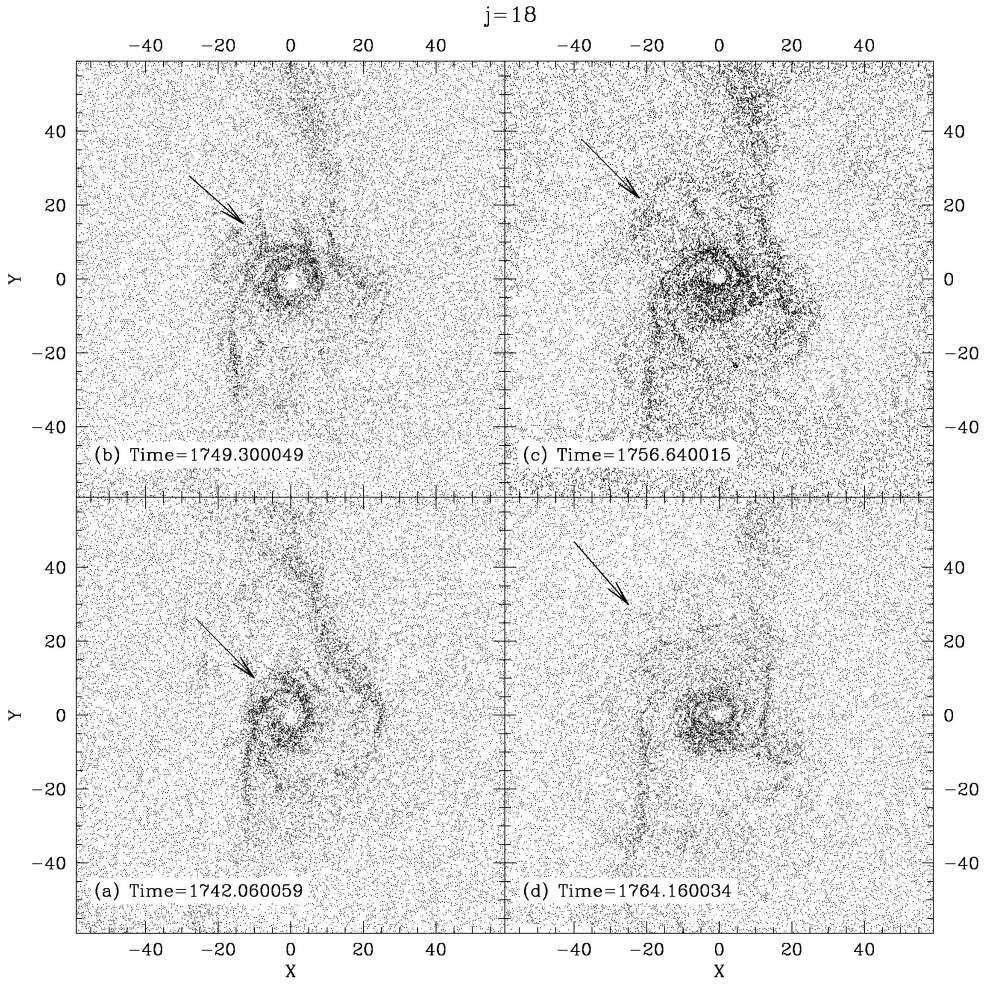
Orbital parameters evolution (sub-Keplerian j=54)

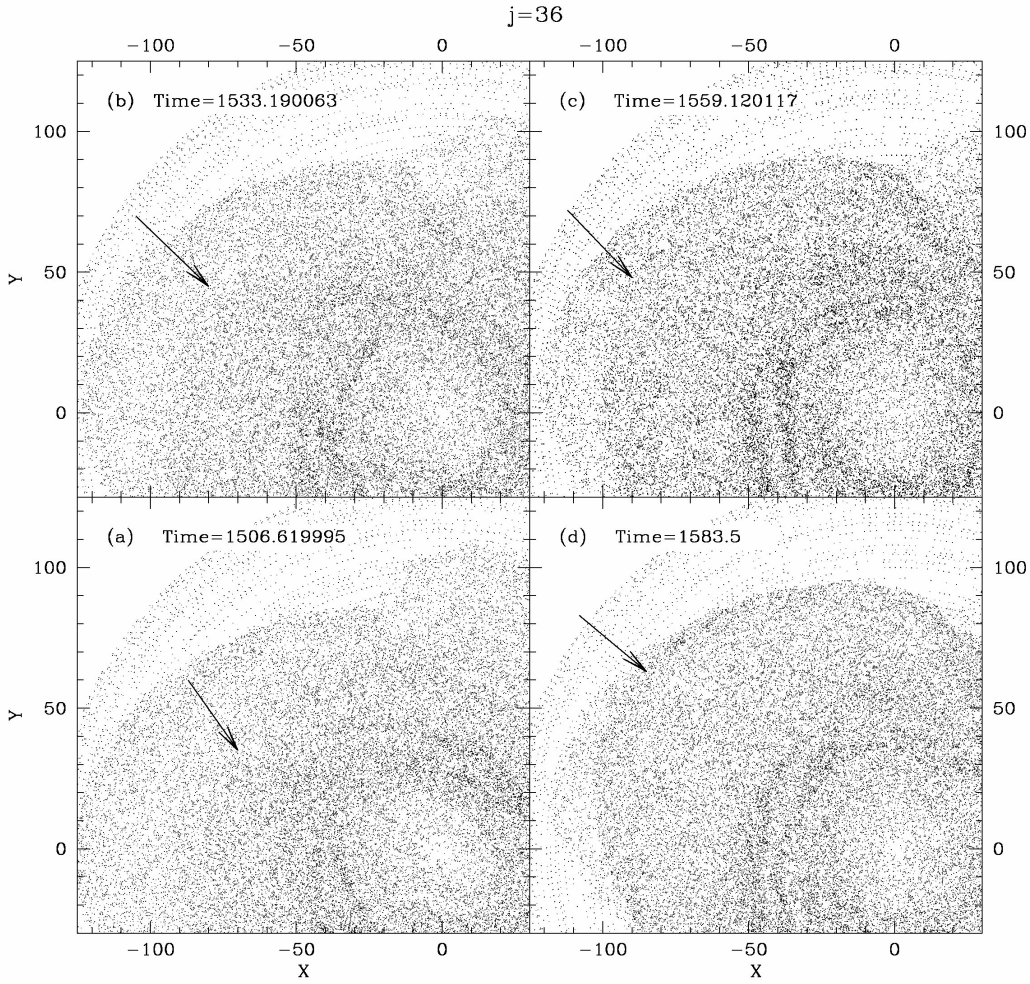
Model	Planet mass	pseudo-atmosphere
a	Jovian	no
b	Jovian	yes
c	Earth	no
d	Earth	yes





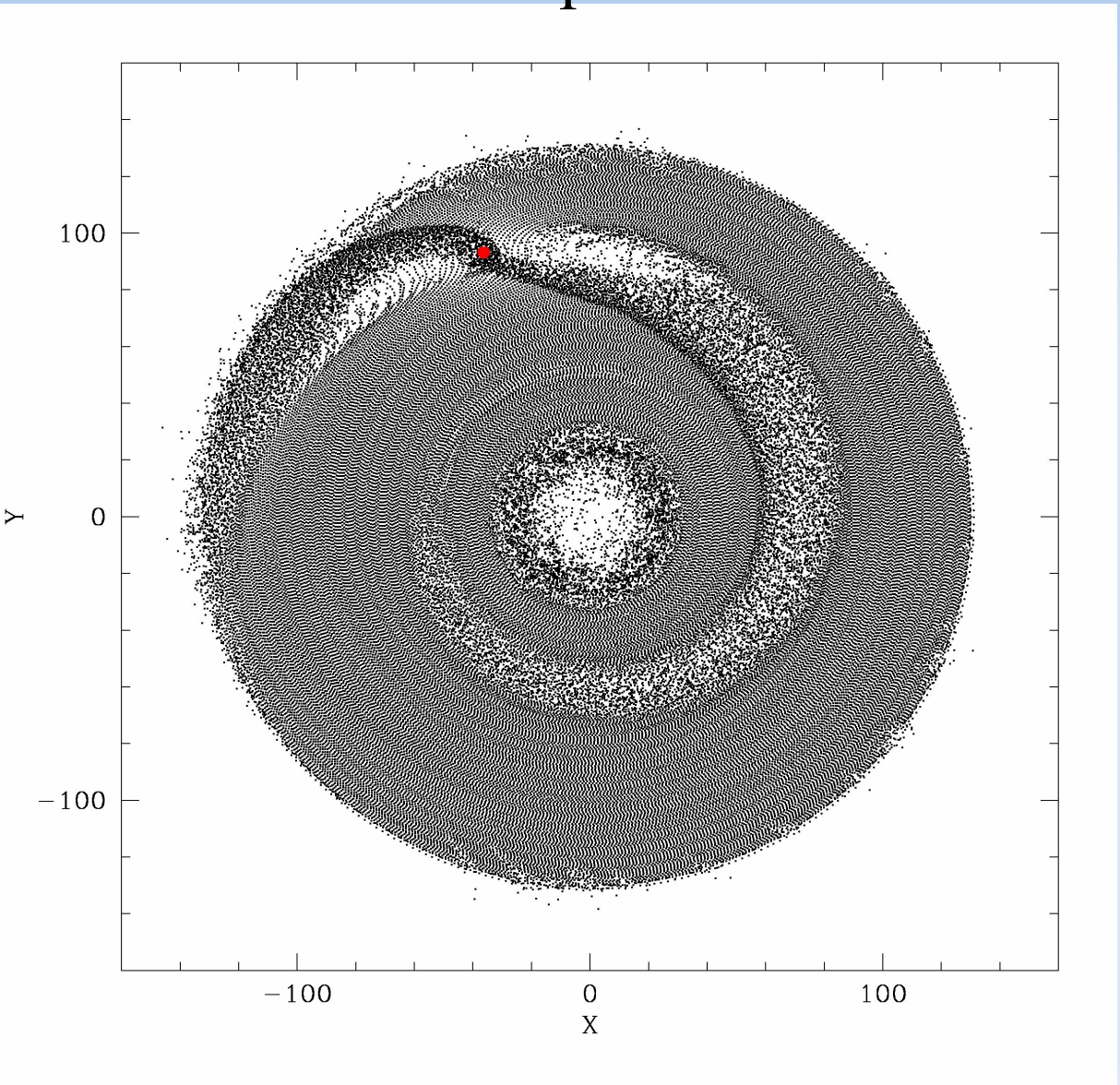
Propagation of waves





Eventual formation of a disc gap in a Keplerian disc

Jovian planet



Future

- Multiplanet simulations, both 2D and 3D (work already in progress)
- Inclusion of physical viscosity
- Radiation effects on the gas (simplified scheme through γ values)
- Real radiation treatment and spectrum formation (<--- long term project)