

Plasma-Dust Coupling in the Heliosphere

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The heliospheric space plasma physics in the era of
multipoint space missions

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Topics of interest...

→ Dust in space

- Where can it be found ?
- Natural sources
- Human made dust
- Danger of space dust

→ Space weather

- Effect on dust dynamics
- Solar wind models
- Interplanetary magnetic field

→ Force models

- Non gravitational forces
- Gauss' equations
- Near Hamiltonian framework

→ Solar radiation

- Poynting-Robertson effect
- Solar radiation pressure
- Solar wind drag

→ Charged dust grains

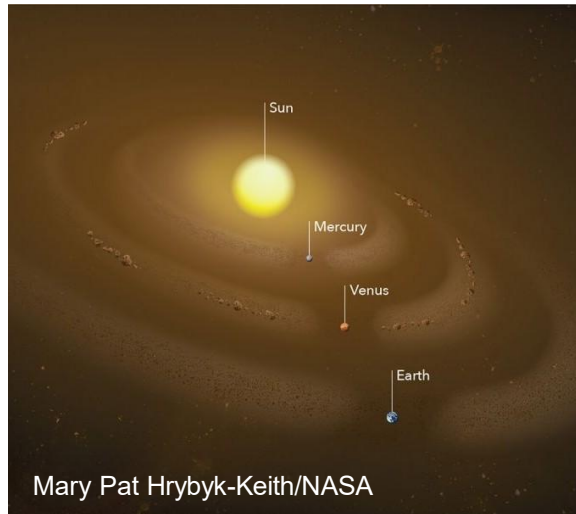
- Charging processes
- Secular evolution
- Distribution, bands

→ Role of resonances

- Mean motion resonances
- Temporary capture
- Stability

Dust in the solar system

Dust rings are found in the solar system and also in exo-planetary systems.



Stenborg et al. 2018, Pokorný & Kuchner 2019

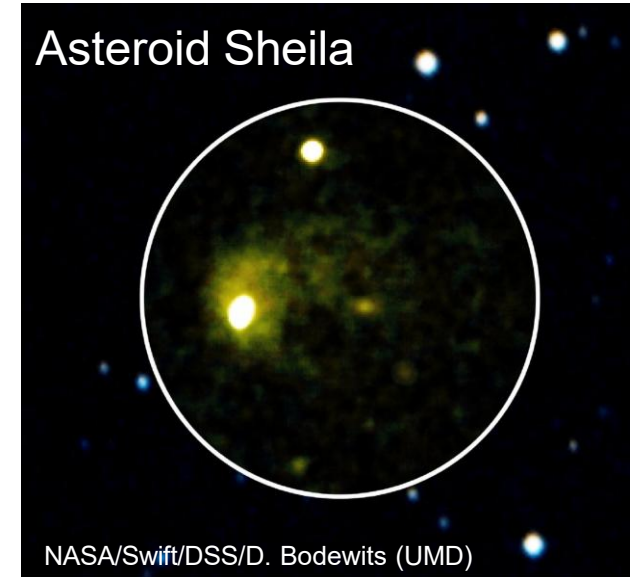
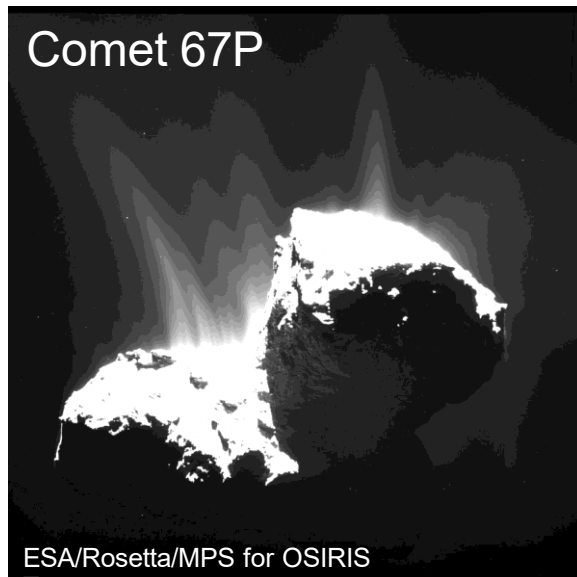
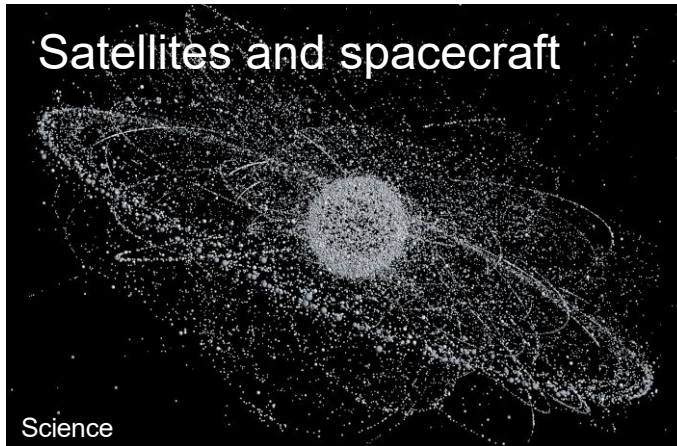


Fedele et al. 2017



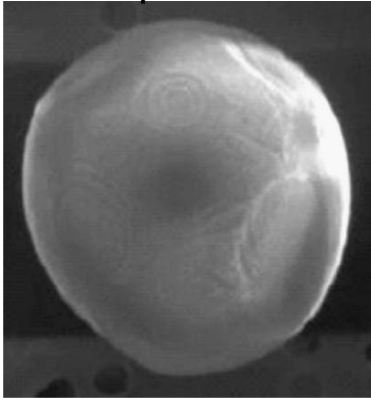
Debris and dust sources

Debris and dust is constantly produced and removed from space

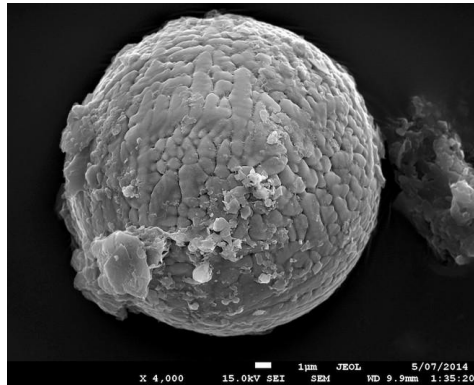


Space debris and space dust

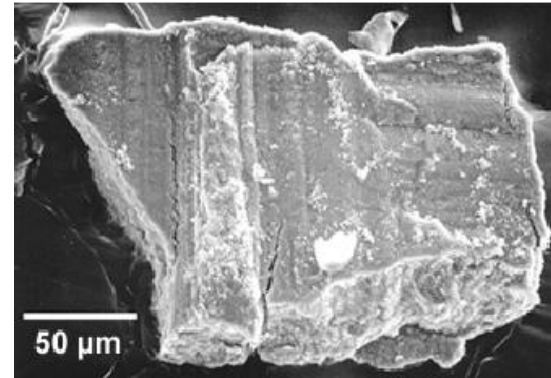
Al₂O₃ particles



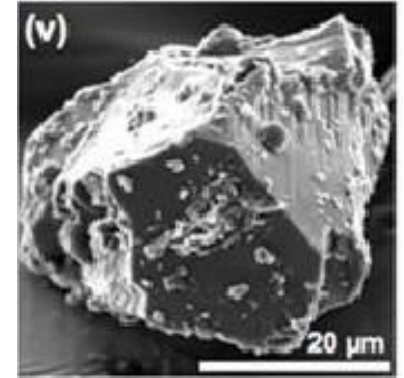
Micrometeorites



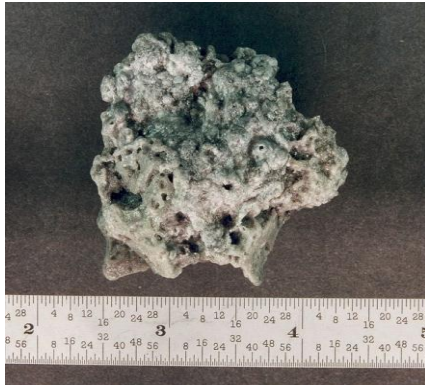
Paint flake



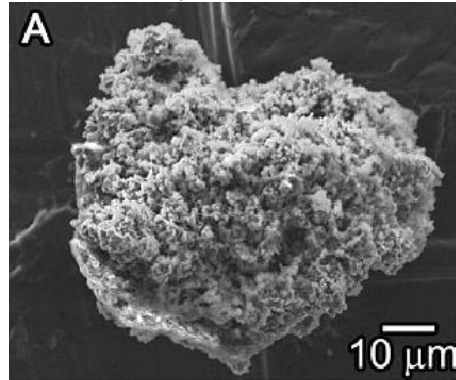
Asteroidal dust



Exhaust slag



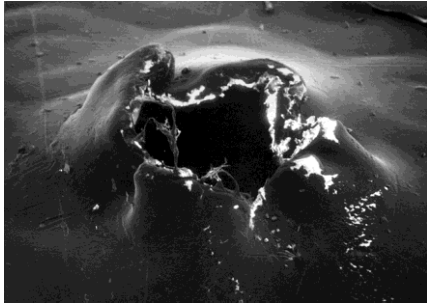
Cometary dust



- 1) Al₂O₃ particles from rocket science lab vs. micrometeorite in 2.7 billion old lime stone in Western Australia
- 2) Paint flake from impactor analysis of Space Shuttle vs. asteroidal dust from 25143 Itokawa, Hayabusa probe

- 3) Exhaust slag from NASA vs. comet dust in antarctic ice near Tottuki Point

Serious damage to spacecraft



Hypervelocity impacts on space shuttle (STS-87) :

Probably due to 0.1mm stainless steel impactor

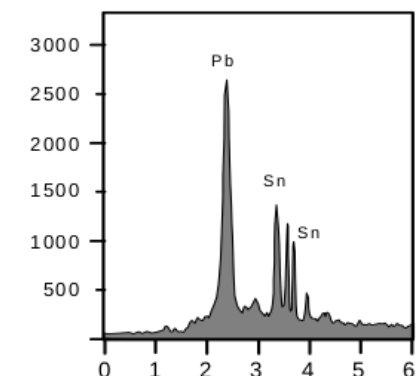
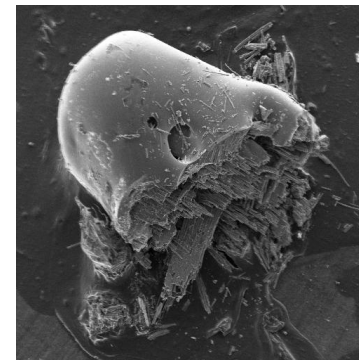
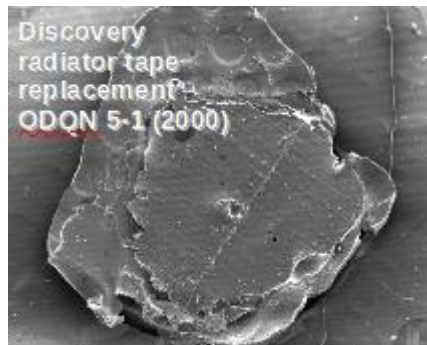
7 impacts with 1mm minimum radius on radiators
(176 impacts on windows)

Damage regions from 0.125 to 3.25mm

Orbital debris 24 vs. meteoroids 28 (out of 52)

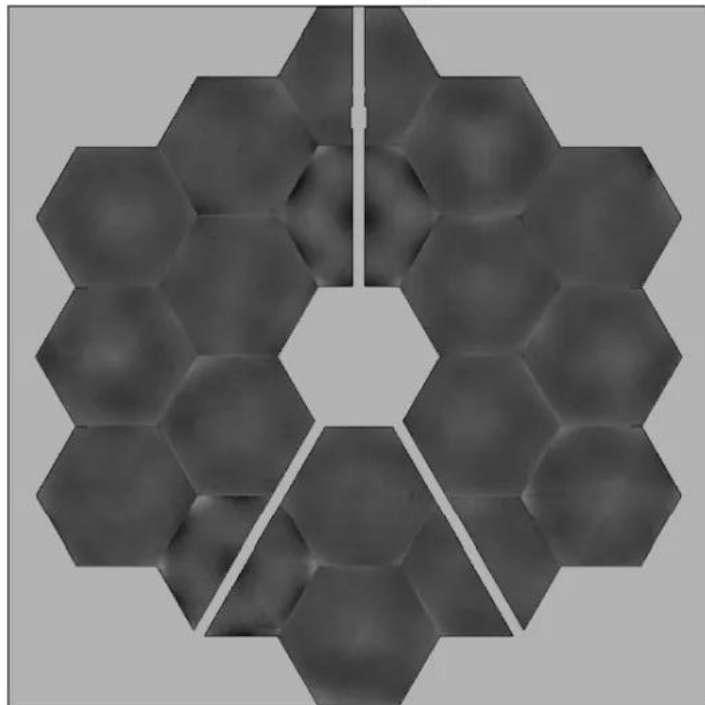
71% aluminum, 21% stainless steel, 8% paint flakes

ODQN 3-4 (1998).



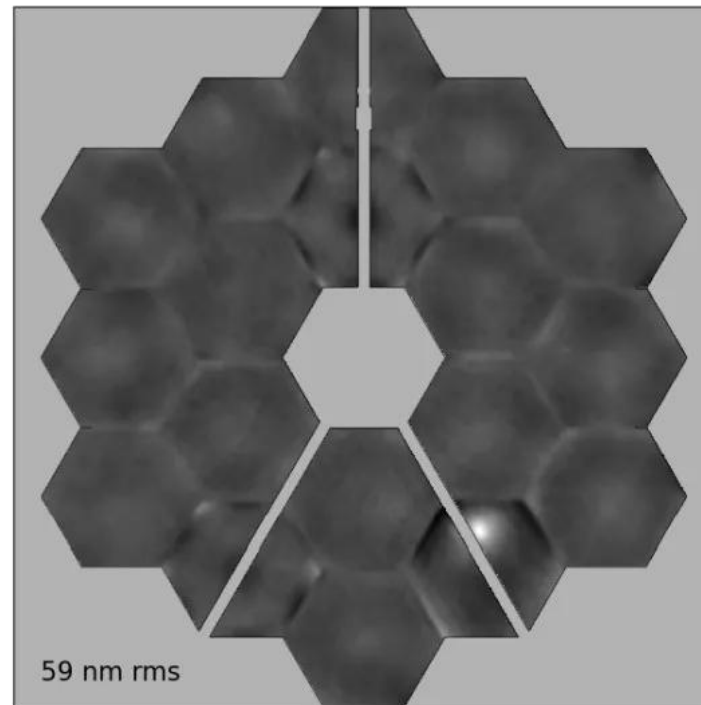
James Webb space telescope

**Ground Measurements for
Individual segments**

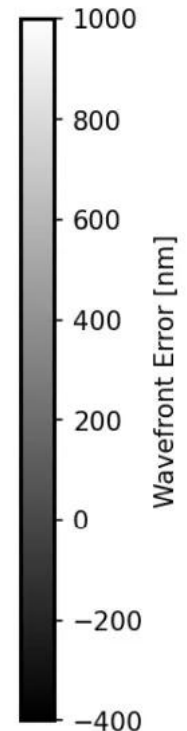


Interferometry measurements from NASA XRCF

Recent Best Mirror Alignment



NIRCam wavefront sensing on 2022-06-21



On the right, the state of the James Webb Space Telescope on June 21, 2022, after an unexpectedly large micrometeoroid strike and subsequent responses, compared to the expected state on the left. (Image credit: NASA/STScI)

Affects space measurements

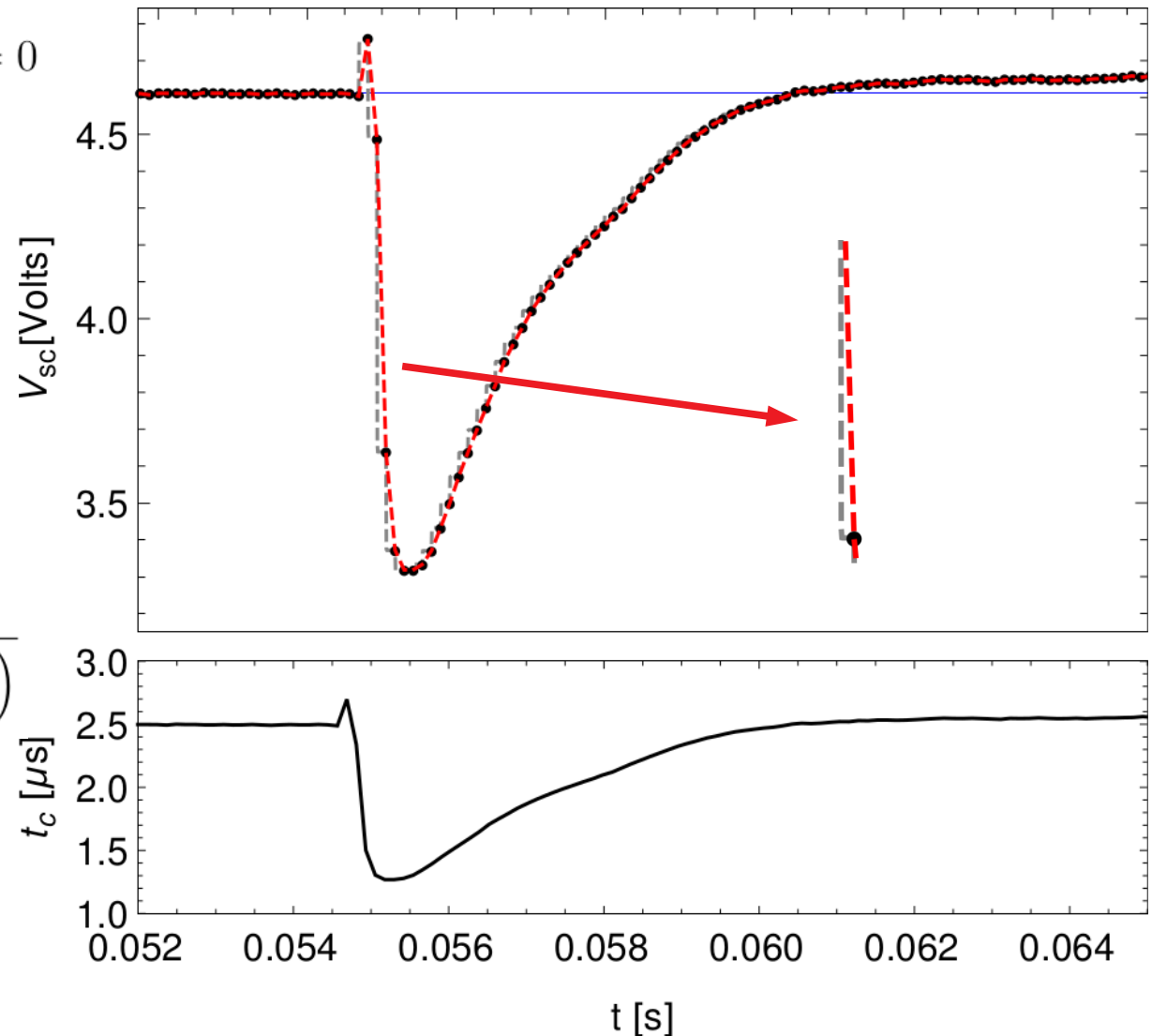
Lhotka et al. 2020

$$1 - \alpha_0 e^{-z_0} - \beta_0 e^{\frac{V_0}{V_1} z_0} + \alpha_1 z_0 = 0$$

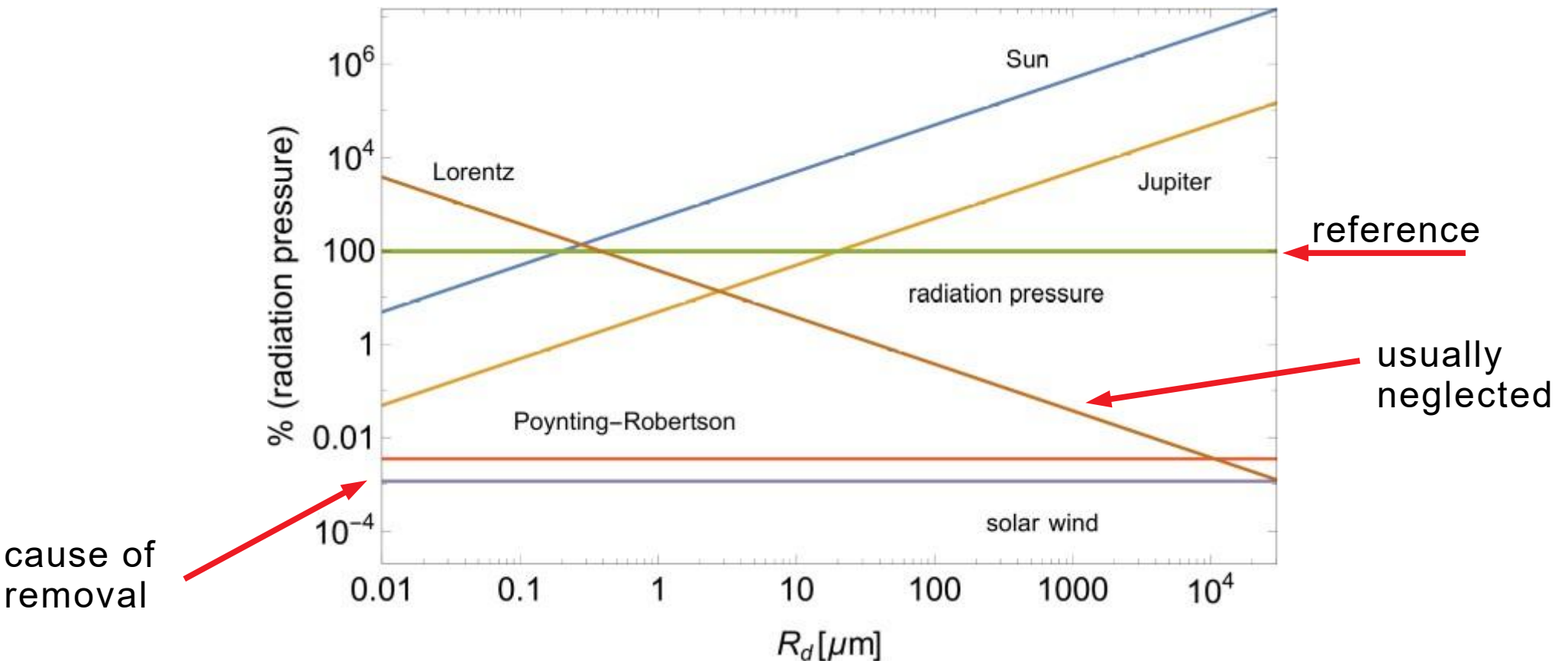
Reconstruction of
spacecraft potential

$$t_c \propto \frac{1}{\alpha_p \left(\alpha_0 e^{-z_0} + \alpha_1 + \beta_0 \frac{V_0}{V_1} e^{-\frac{V_0}{V_1} z_0} \right)}$$

Charging time scale
- time series

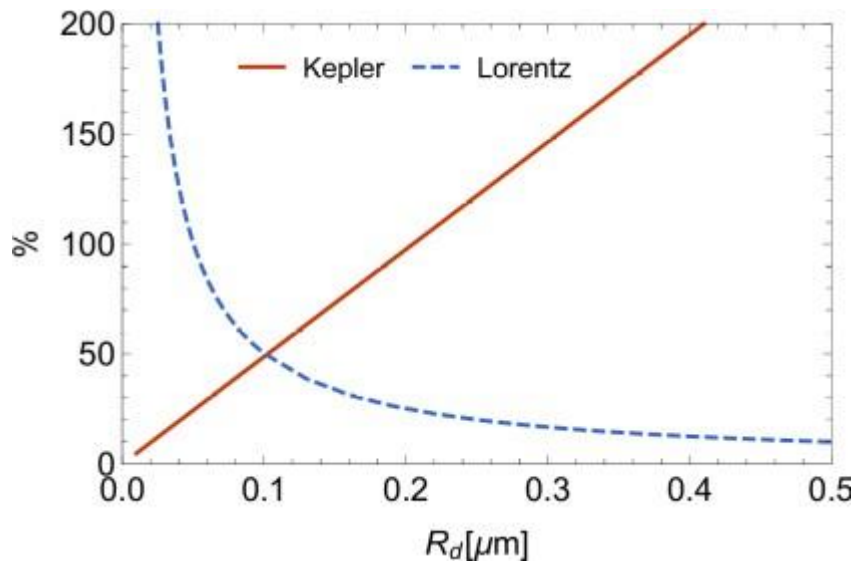


Forces, orbital motion

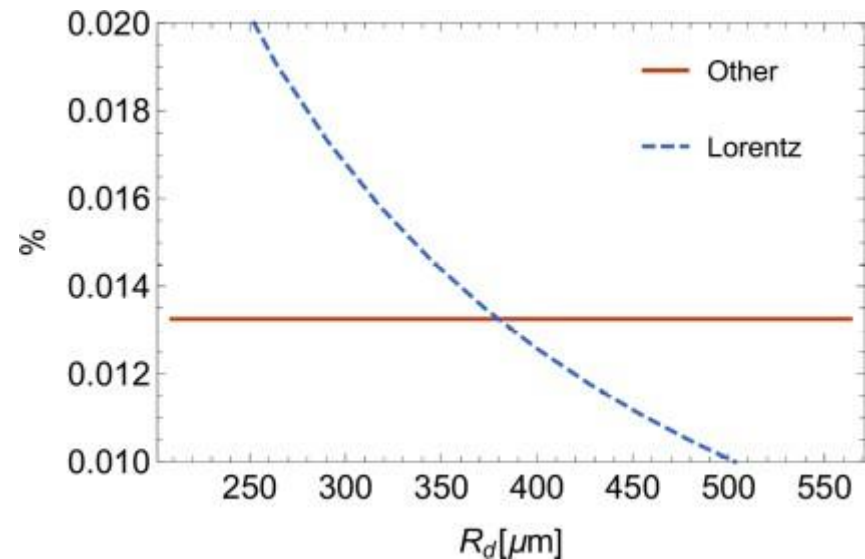
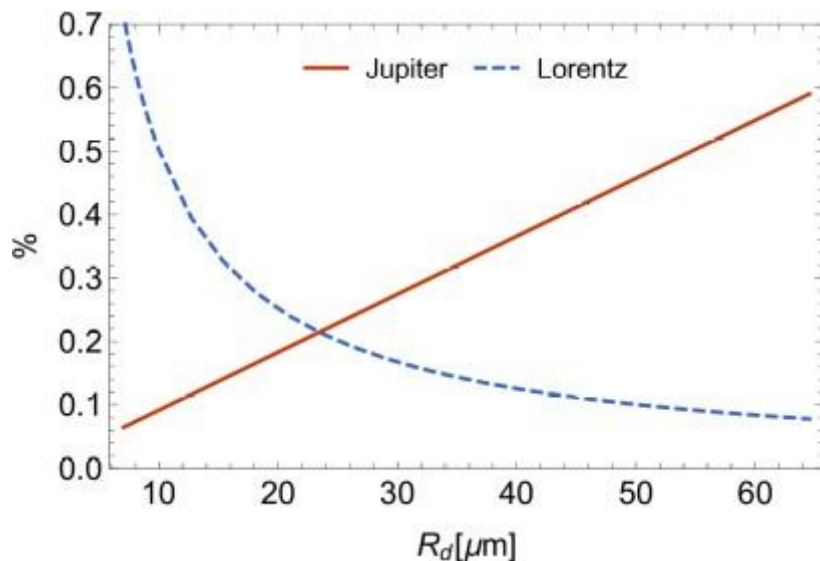


Force magnitudes evaluated for dust grains with 2.8 gcm^{-3} density at a distance of 8AU from the sun (depends on distance etc..)

Lorentz force, really ?

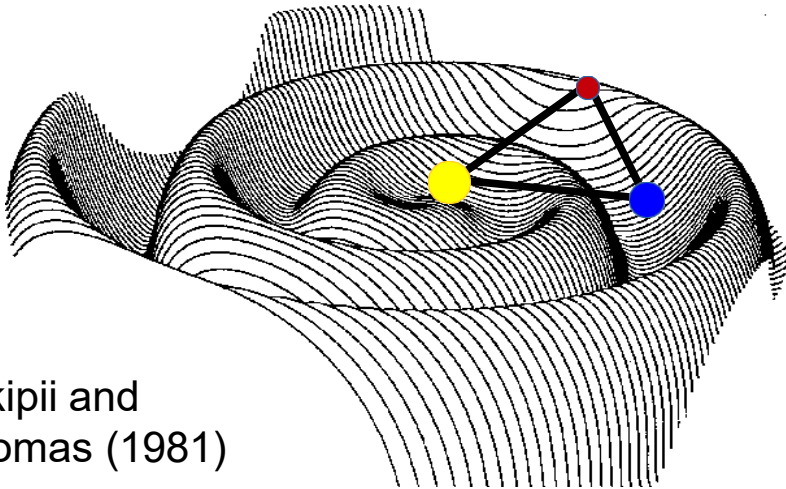


- Lorentz force is stronger in magnitude than central gravity for tiny particles
- Solar radiation pressure is dominant still for smaller particles
- Effect of Jupiter (evaluated at Earth orbit) is weaker for micro-meter sized particles than LF
- Lorentz force is the dominant non-gravitational force up to 400 micro-meters (without SRP)



Dynamics in the solar system

Charged particle subject to planet, solar wind, and interplanetary magnetic field:



Jokipii and
Thomas (1981)

$$\frac{d\mathbf{v}}{dt} = -\frac{(1-\beta)\mu}{r^2}\mathbf{e}_R - \frac{\beta\mu^{(1)}}{r^2}\left(1 + \frac{\eta}{Q}\right)\left(\frac{(\mathbf{v}\cdot\mathbf{e}_R)\mathbf{e}_R + \mathbf{v}}{c}\right) - Gm_1^{(3)}\left(\frac{\mathbf{r}_1}{r_1^3} + \frac{\mathbf{r} - \mathbf{r}_1}{\|\mathbf{r} - \mathbf{r}_1\|^3}\right) + \frac{q}{m}(\mathbf{v} - \mathbf{u}_{sw}) \times \mathbf{B}^{(4)},$$

Gravitational attraction of the sun (1), Poynting-Robertson and solar wind drag (2), the attraction of an additional planet (3), and Lorentz force due to the interplanetary magnetic field (4)

- Effect of (1) : two body motion with reduced central mass.
- Effect of (2) : e.g, inward drift in semi-major axis due to loss of orbital energy.
- Effect of (3) : e.g., temporary capture in orbital resonance with the planets.
- Effect of (4) : e.g., inward/outward drift in semi-major axis / off plane motion.

Dynamics around planets

Poynting-Robertson and solar wind drag in the space debris problem :



$$\begin{aligned}\ddot{\mathbf{x}} = & V_x(x, y, z, \theta) - \mathcal{G}m_S \left(\frac{x - x_S}{|\mathbf{r} - \mathbf{r}_S|^3} + \frac{x_S}{r_S^3} \right) \\ & - \mathcal{G}m_M \left(\frac{x - x_M}{|\mathbf{r} - \mathbf{r}_M|^3} + \frac{x_M}{r_M^3} \right) + \beta \mathcal{G}m_S \frac{x - x_S}{|\mathbf{r} - \mathbf{r}_S|^3} \\ & - \frac{\beta \mathcal{G}m_S}{c} \left(1 + \frac{\eta}{Q} \right) \left\{ \frac{x - x_S}{|\mathbf{r} - \mathbf{r}_S|^3} (\dot{x} - \dot{x}_S) + \frac{\dot{x} - \dot{x}_S}{|\mathbf{r} - \mathbf{r}_S|^2} \right\}\end{aligned}$$

Force (per unit mass) due to *gravitational potential of the Earth (1)*, *Sun's gravity (2)*, the *attraction of the Moon (3)*, *solar radiation pressure (4)*, *Poynting-Robertson drag (5)*, and *solar wind drag (6)*.

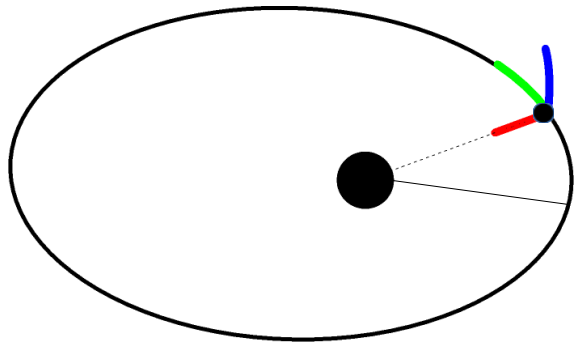
Effect of (5) + (6) :

- Leads to drift in semi-major axis a
- Shifts the location of resonant equilibria, i.e. the location of geostationary orbit
- May render stationary orbits unstable and leads to temporary capture

Gauss' planetary equations of motions

Perturbation theory in Gauss form of equations of motion :

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^2} \mathbf{e}_R + \mathbf{F}(\mathbf{r}, \dot{\mathbf{r}}, r, \dot{r}, \cos\psi, \dots)$$



radial $\mathbf{o}_R = (\cos f, \sin f, 0)$
tangential $\mathbf{o}_T = (-\sin f, \cos f, 0)$
normal $\mathbf{e}_N = \mathbf{o}_R \times \mathbf{o}_T$

force system

$$\mathfrak{F} = \mathfrak{F}_R \mathbf{o}_R + \mathfrak{F}_T \mathbf{o}_T + \mathfrak{F}_N \mathbf{o}_N$$

Local force system attached to celestial body

$$\frac{da}{dt} = \frac{2ah}{\mu(1-e^2)} [e \sin f \mathfrak{F}_R + (1 + e \cos f) \mathfrak{F}_T],$$

$$\frac{de}{dt} = \frac{h}{\mu} [\sin f \mathfrak{F}_R + (\cos f + \cos E) \mathfrak{F}_T],$$

$$\frac{di}{dt} = \frac{\cos(\omega + f)r}{h} \mathfrak{F}_N,$$

$$\begin{aligned} \frac{d\omega}{dt} = & -\frac{h}{\mu e} \left[\cos f \mathfrak{F}_R - \left(\frac{2 + e \cos f}{1 + e \cos f} \right) \sin f \mathfrak{F}_T \right] \\ & - \frac{\cos i \sin(\omega + f)r \mathfrak{F}_N}{h \sin i}, \end{aligned}$$

$$\frac{d\Omega}{dt} = \frac{\sin(\omega + f)r}{h \sin i} \mathfrak{F}_N,$$

$$\begin{aligned} \frac{dM}{dt} = & n + \frac{h}{\mu} \frac{\sqrt{1-e^2}}{e} \left[\left(\cos f - \frac{2e}{1-e^2} \frac{r}{a} \right) \mathfrak{F}_R \right. \\ & \left. - \left(1 + \frac{1}{1-e^2} \frac{r}{a} \right) \sin f \mathfrak{F}_T \right]. \end{aligned}$$

Near Hamiltonian system

Many applications in celestial mechanics can be described by nearly integrable, weakly dissipative systems :

Hamiltonian dynamics:

analytic, regular functions H_0, H_1

$$H(y, x, t) = H_0(y) + \varepsilon H_1(y, x, t)$$

$y \in \mathbb{R}^\ell, (x, t) \in \mathbb{T}^{\ell+1}$ action-angle like variables

fundamental frequencies:

for $\varepsilon = 0$ integrable:

$$\omega(y) = \partial H_0(y) / \partial y$$

$$\begin{aligned} x(t) &= x(0) + \omega(y(0))t \\ y(t) &= y(0), \end{aligned}$$

Nearly Hamiltonian = weakly dissipative:

$$H(y, x, t) = h_{00}(y) + \varepsilon h_{10}(y, x, t)$$

→ for $\varepsilon = 0$ dissipative, possibly integrable

$$\dot{x} = \omega(y) + \varepsilon h_{10,y}(y, x, t) + \mu f_{01}(y, x, t)$$

→ for $\mu = 0$ conservative

$$\dot{y} = -\varepsilon h_{10,x}(y, x, t) + \mu (g_{01}(y, x, t) - \eta(y, x, t))$$

→ for $\varepsilon = \mu = 0$ integrable

drift function:

analytic, regular functions h_{10}, f_{01}, g_{01}

$$\eta = \eta(y, x, t)$$

Tools from Hamiltonian dynamics are useful also for dissipative systems (and vice versa).

Gravity

gravitational parameter

mass of dust

mass of secondary

mass of primary

secondary's distance

distance of dust from primary

$$\mathbf{F}_g = -\frac{\mu m}{r^3} \mathbf{r} - \frac{\mu m_1 m}{m_0} \left(\frac{\mathbf{r}_1}{r_1^3} + \frac{\mathbf{r} - \mathbf{r}_1}{\|\mathbf{r} - \mathbf{r}_1\|^3} \right)$$

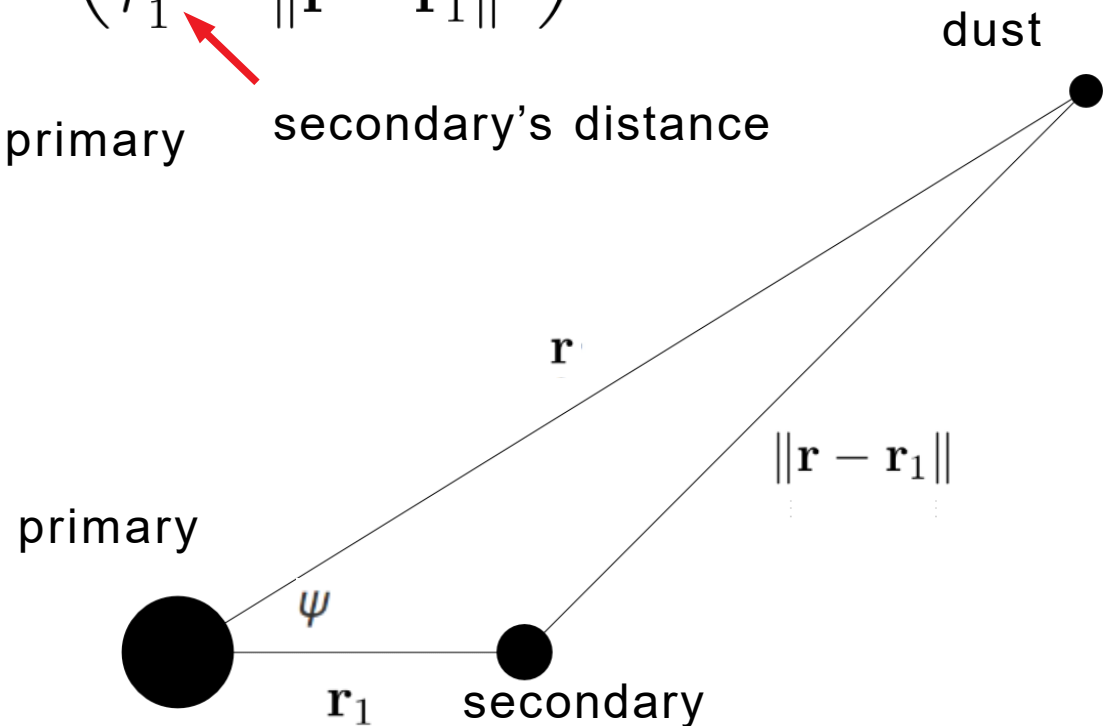
Basic model: spatial restricted three-body problem

In solar system dynamics:

- primary : sun
- secondary : Jupiter

Extra-planetary systems:

- primary : star
- secondary : main planet



Solar radiation

$$\mathbf{F}_{s/p} = -\nabla \frac{\mu m \beta}{r} - \frac{\mu m \beta}{r^2} \left(1 + \frac{\eta}{Q} \right) \left(\frac{(\dot{\mathbf{r}} \cdot \mathbf{g}_r) \mathbf{g}_r + \dot{\mathbf{r}}}{c} \right)$$

solar radiation
 solar gravity
 mass of dust
 solar wind factor
 velocity vector
 gravitational parameter
 efficiency factor
 speed of light
 radial unit vector
 distance of dust from primary

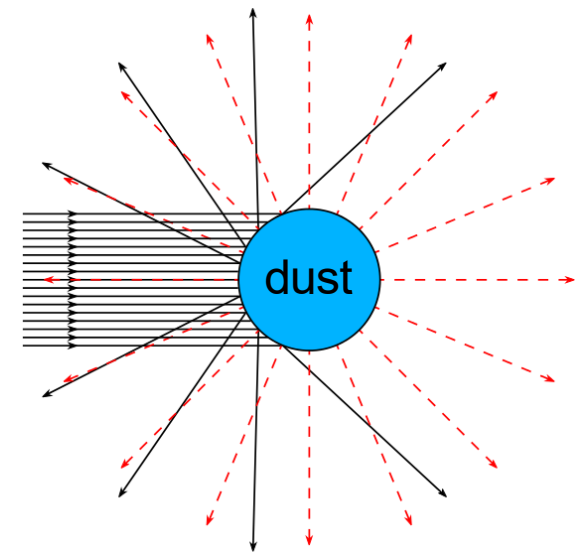
relativistic derivation:

$$\frac{dp_{in}^{\mu}}{d\tau} = \frac{w^2 SA' \bar{Q}'_{ext}}{c} b^{\mu} \quad \tau \text{ proper time}$$

$$\frac{dp_{out}^{\mu}}{d\tau} = \frac{w^2 SA' \bar{Q}'_{ext}}{c} \left[\bar{Q}' \frac{u^{\mu}}{c} + (1 - \bar{Q}') b^{\mu} \right] \quad \text{Newtonian approximation:}$$

$$\frac{dp^{\mu}}{d\tau} = \frac{dp_{in}^{\mu}}{d\tau} - \frac{dp_{out}^{\mu}}{d\tau} \quad \text{equation of motion} \longrightarrow \boxed{\frac{d\vec{v}}{dt} = \frac{SA' \bar{Q}'_{pr}}{mc} \left[\left(1 - \frac{\vec{v} \cdot \vec{e}}{c} \right) \vec{e} - \frac{\vec{v}}{c} \right]}$$

incident photons



Klacka et al. 2014

Space plasma

velocity vector

(interplanetary) magnetic field

solar wind speed magnitude

charge

solar wind speed

radial unit vector

$$(1) \quad \mathbf{F}_L = q (\dot{\mathbf{r}} - \mathbf{u}_{sw}) \times \mathbf{B}$$

$$\mathbf{u}_{sw} = u_{sw} \mathbf{g}_r$$

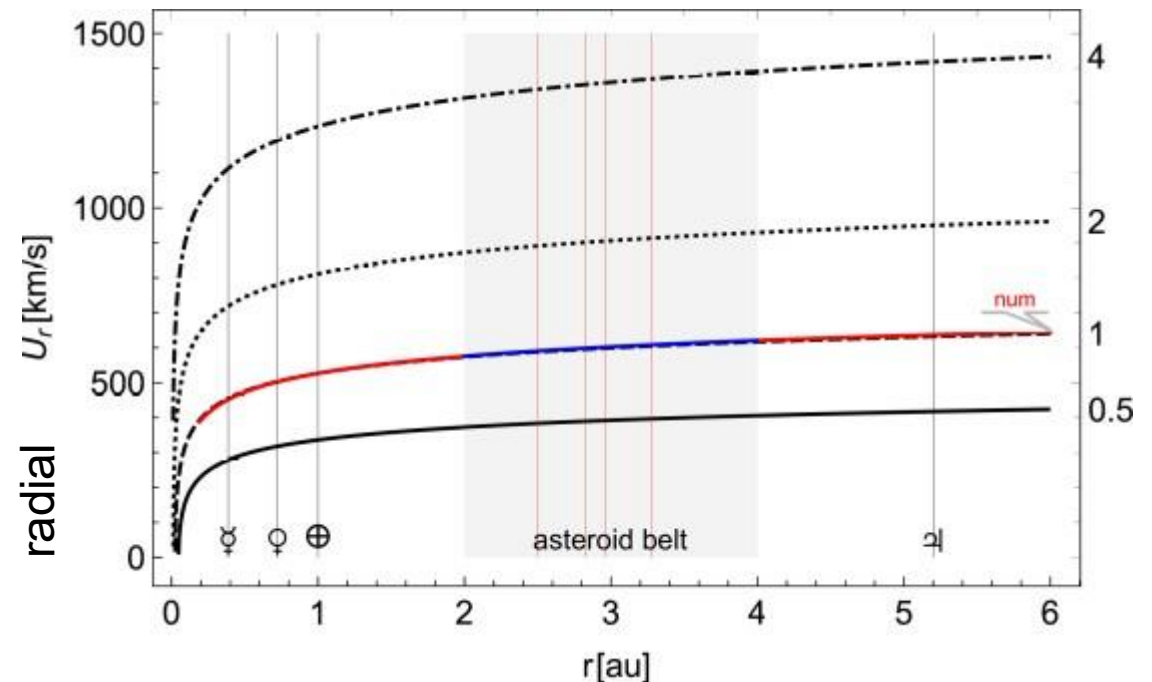
Lorentz force:

$$\mathbf{F}_L = q (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (2)$$

Frozen-in electric field in the solar wind:

$$\mathbf{E} = -\mathbf{u}_{sw} \times \mathbf{B}$$

Transforms (2) into (1)



Lhotka & Narita 2019

Lorentz force

background field

charge

reference distance

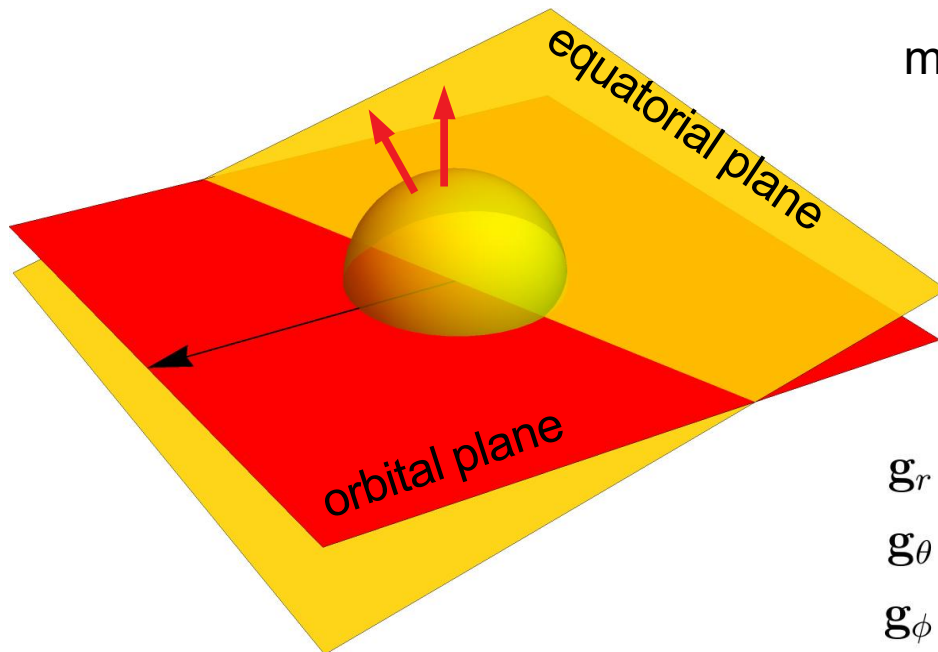
sun rotation rate

velocity vector

solar distance

solar wind speed

$$\mathbf{F}_L = -\frac{qB_0r_0^2}{r^2} \left[\frac{1}{r} \mathbf{r} \times \dot{\mathbf{r}} + \frac{\Omega_s}{r} \mathbf{r} \times (\mathbf{r} \times \mathbf{g}_{\tilde{z}}) + \frac{\Omega_s}{u_{sw}} (\mathbf{r} \times \mathbf{g}_{\tilde{z}}) \times \dot{\mathbf{r}} \right] \tanh\left(\alpha \frac{\mathbf{r} \cdot \mathbf{g}_{\tilde{z}}}{r}\right)$$



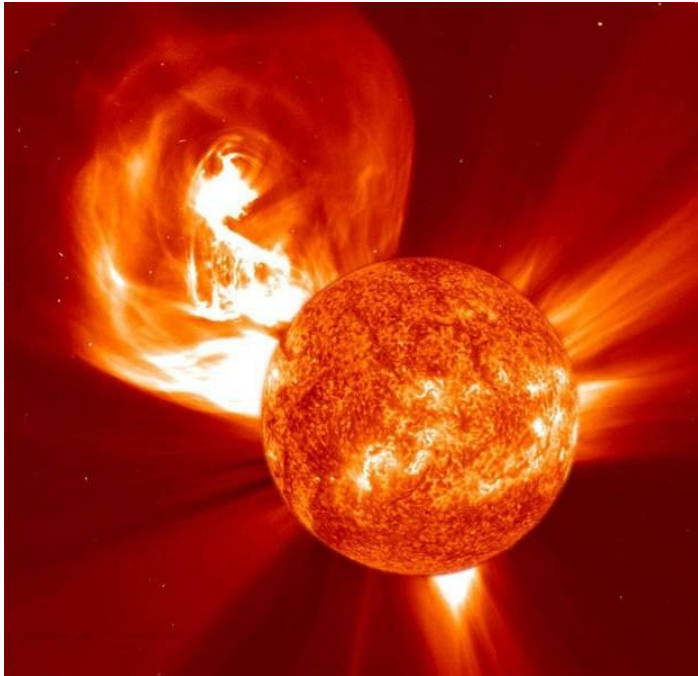
sign change function

$$\mathbf{B} = \frac{Af(\theta)}{r^2} \left(\mathbf{g}_r - \frac{\Omega_s r \sin(\theta)}{u_{sw}} \mathbf{g}_\phi \right)$$

$$\begin{aligned} \mathbf{g}_r &= \sin(\theta) [\cos(\phi) \mathbf{g}_{\tilde{x}} + \sin(\phi) \mathbf{g}_{\tilde{y}}] + \cos(\theta) \mathbf{g}_{\tilde{z}} , \\ \mathbf{g}_\theta &= \cos(\theta) [\cos(\phi) \mathbf{g}_{\tilde{x}} + \sin(\phi) \mathbf{g}_{\tilde{y}}] - \sin(\theta) \mathbf{g}_{\tilde{z}} , \\ \mathbf{g}_\phi &= -\sin(\phi) \mathbf{g}_{\tilde{x}} + \cos(\phi) \mathbf{e}_{\tilde{y}} . \end{aligned}$$

Lhotka & Gales 2019

Space weather and solar activity



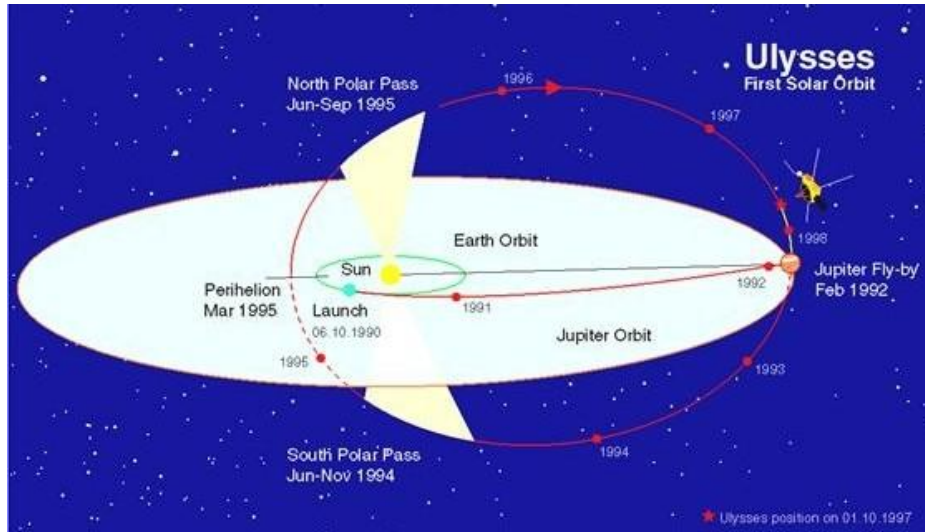
SOHO (NASA and the ESA)

- Source is sun's energy
- Energy released into space in the form of :
 - Light (photons)
 - Atomic particles (ions, electrons, etc..)
 - Magnetic fields
- Typical activity cycles to remember :
 - 27 days (solar rotation period)
 - ~100 days (active region development time scale)
 - Solar cycles : 11 years (22 years, 88 years)
- Heliosphere is the sphere of influence of the sun
- Magnetosphere: created by planetary magnetic fields
 - Deformation by the solar wind
 - Electrons and protons trapped on magnetic field lines

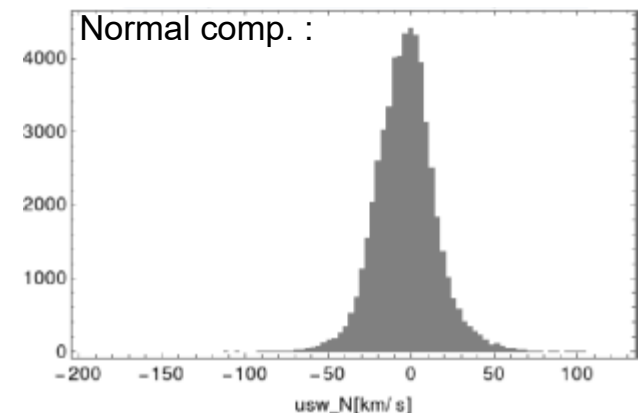
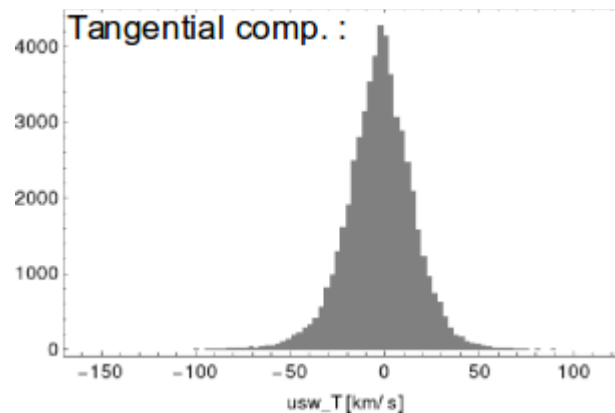
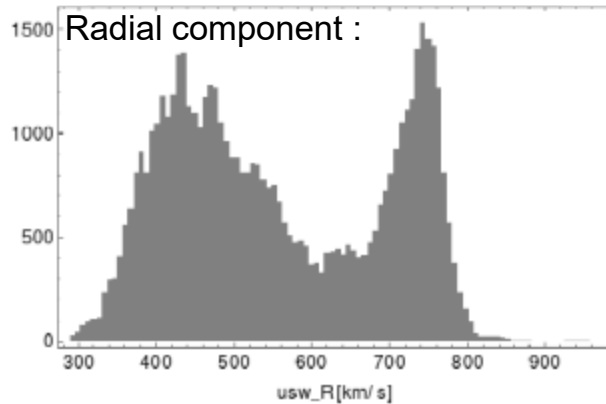
Typical space weather events are:

- X-ray bursts & EUV radiation [8 minutes to reach us]
- Radiation storms (energetic, atomic particles) [15min to 24 hours]
- Geomagnetic storms (triggered by coronal mass ejections that reach the earth) [1-4 days]

Solar wind measurements



- Ulysses spacecraft with primary mission to orbit the Sun at all (i.e. high) latitudes
- Orbital parameters:
 - $a=3.37\text{au}$ (6.2 years orbital period)
 - $e=0.6$
 - $i=80^\circ$ with respect to Sun's equator
- Launch 1990, 17 years operation
- 3 orbits around the Sun
- Fastest ever flown spacecraft until New Horizons
- Joint mission NASA and ESA



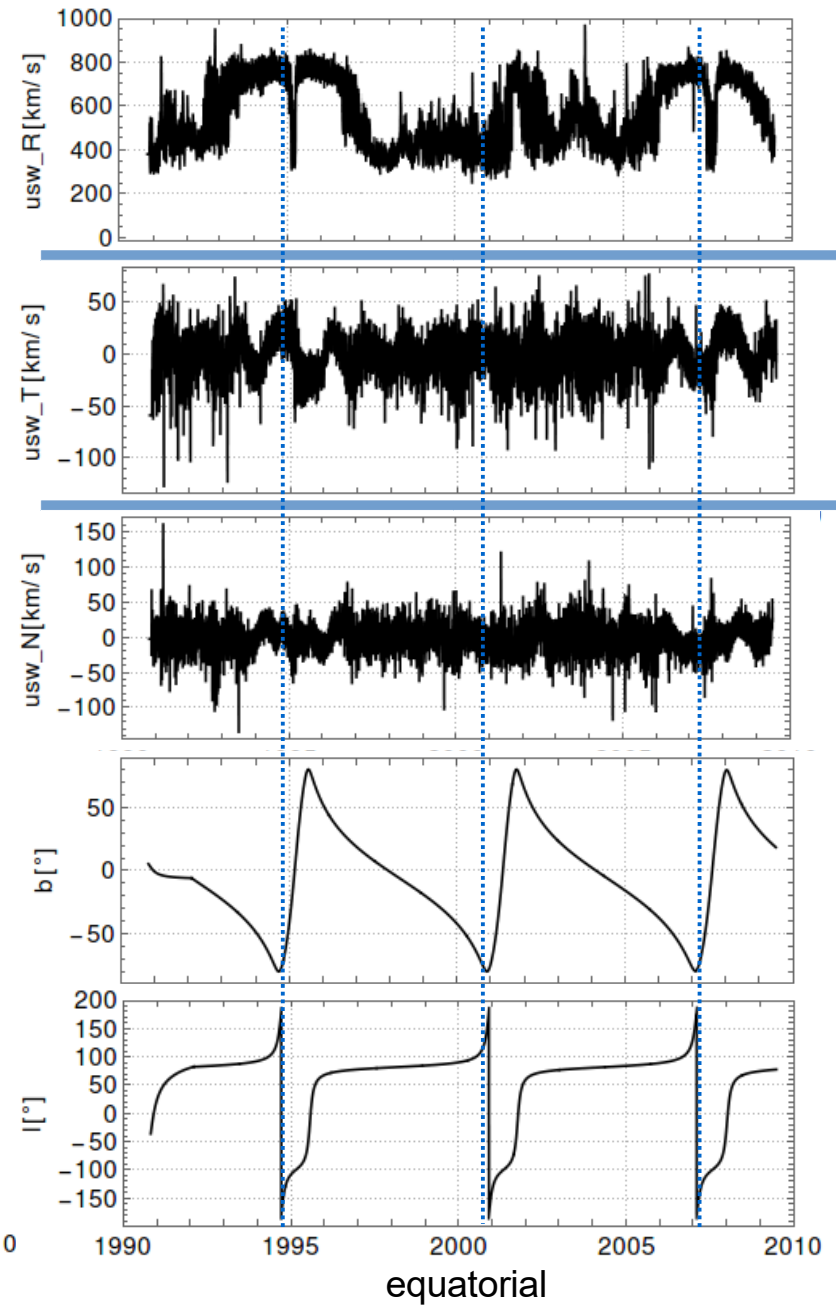
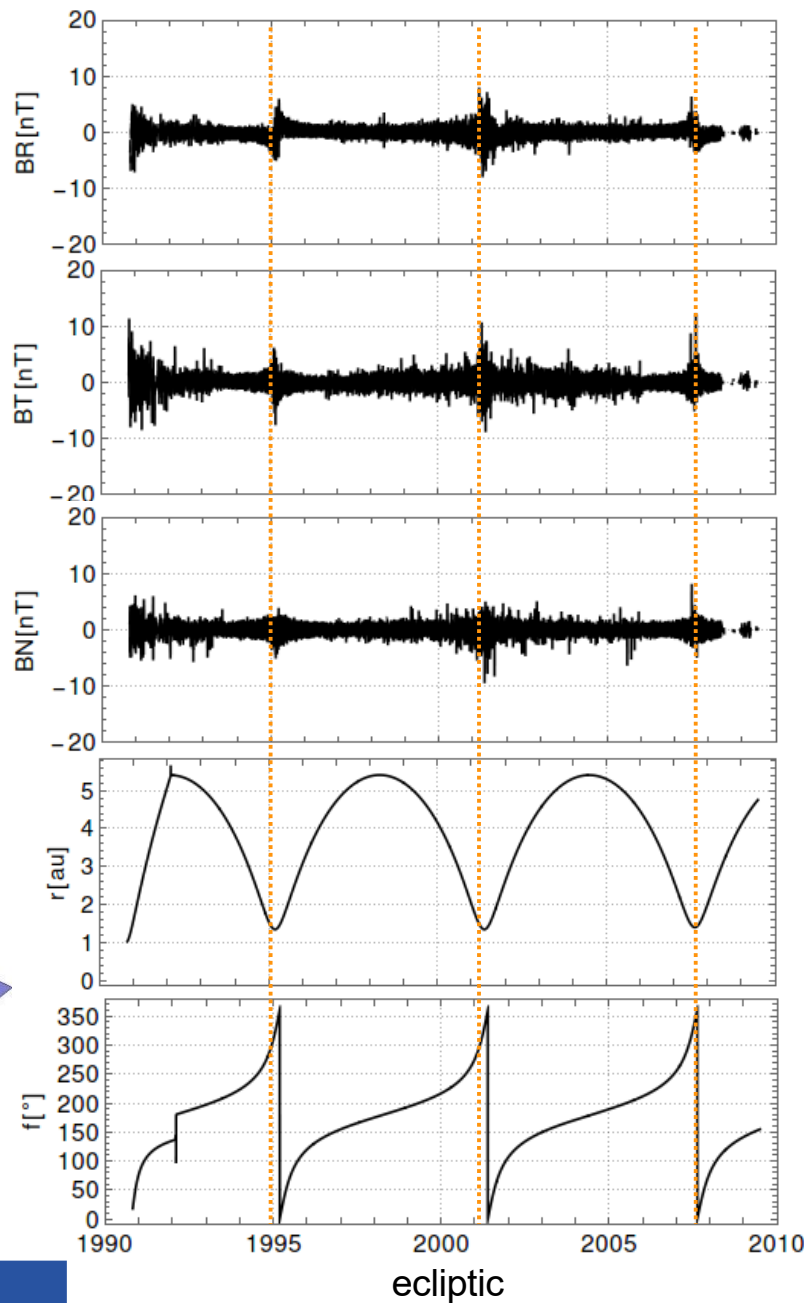
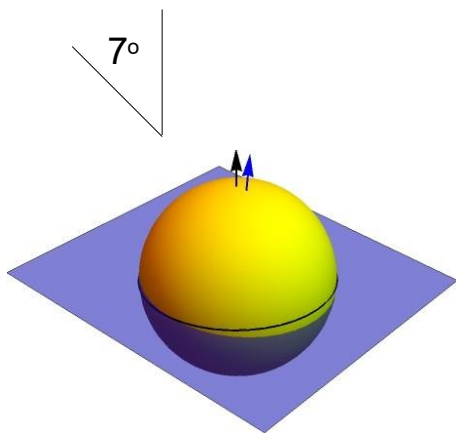
- Variations in density, temperature and speed over time and solar longitude and latitude
- Slow (origin corona) vs. fast (origin coronal holes) solar wind
- Density of slow solar wind = twice density of fast solar wind

Magnetic field

Radial component :

Tangential comp. :

Normal comp. :



Heliospheric field

background field strength

sign change function

sun rotation rate

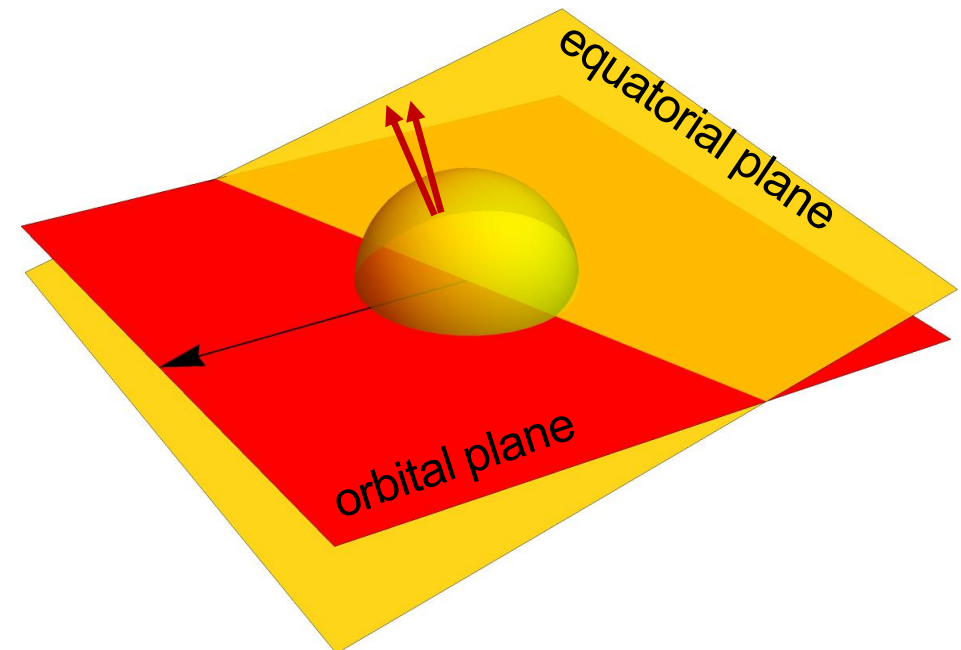
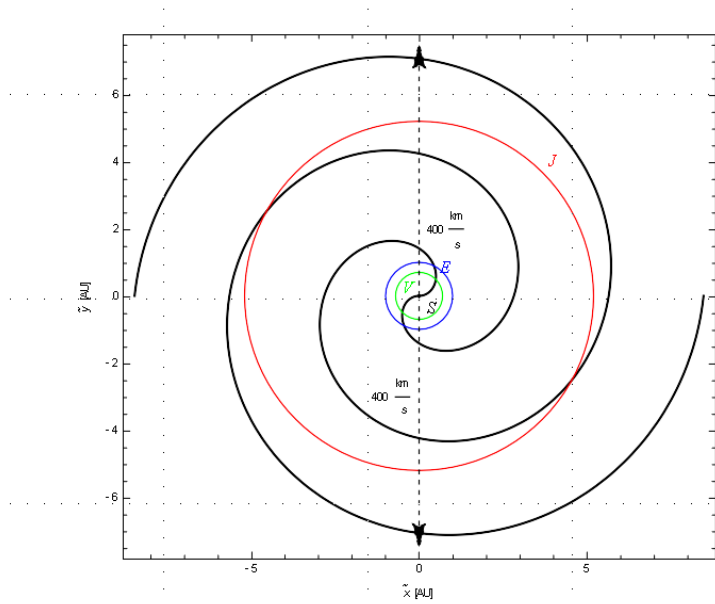
longitudinal component

$$\mathbf{B} = \frac{Af(\theta)}{r^2} \left(\mathbf{g}_r - \frac{\Omega_s r \sin(\theta)}{u_{sw}} \mathbf{g}_\phi \right)$$

solar distance

radial component

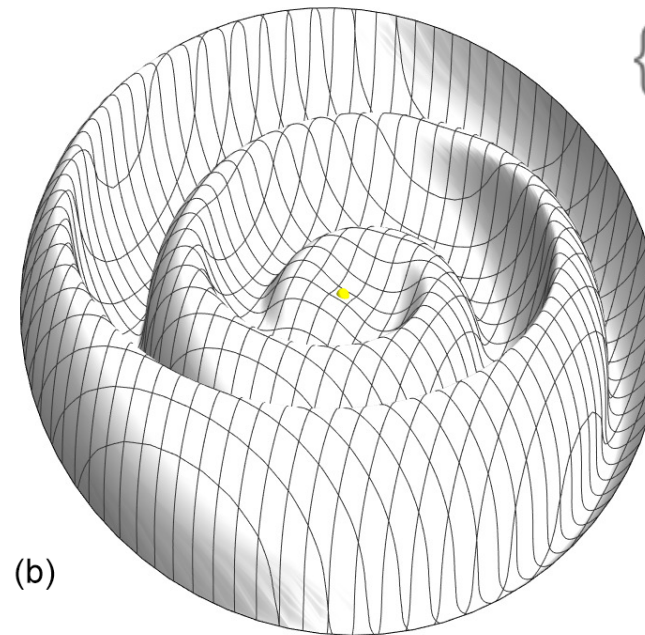
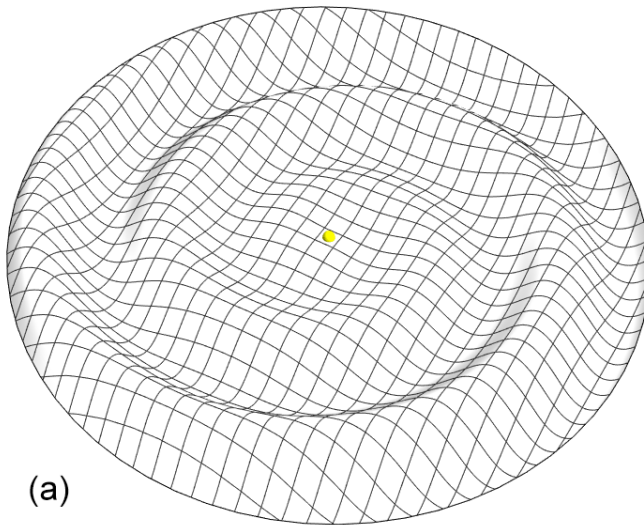
solar wind speed



Polarity and tilt angle

Polarity of the IMF (inwards and outwards) above and below the current sheet together with the tilt of the solar rotation axis form a wavy current sheet, the so-called ballerina skirt model.

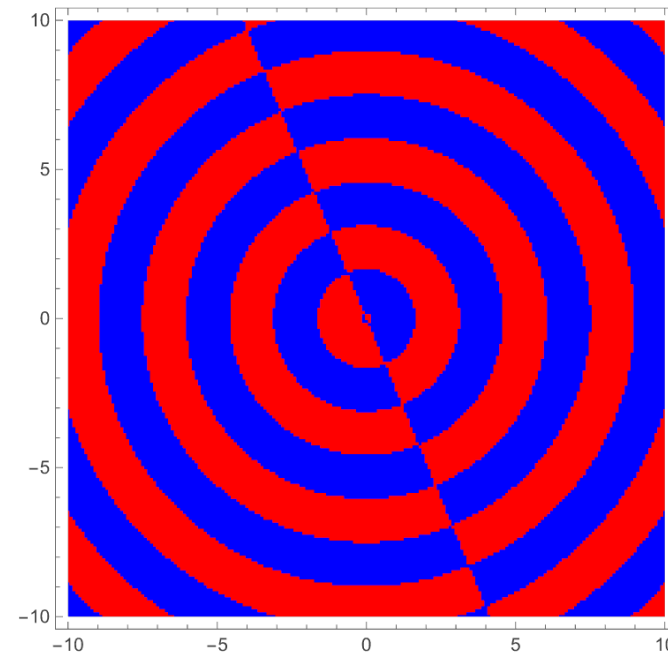
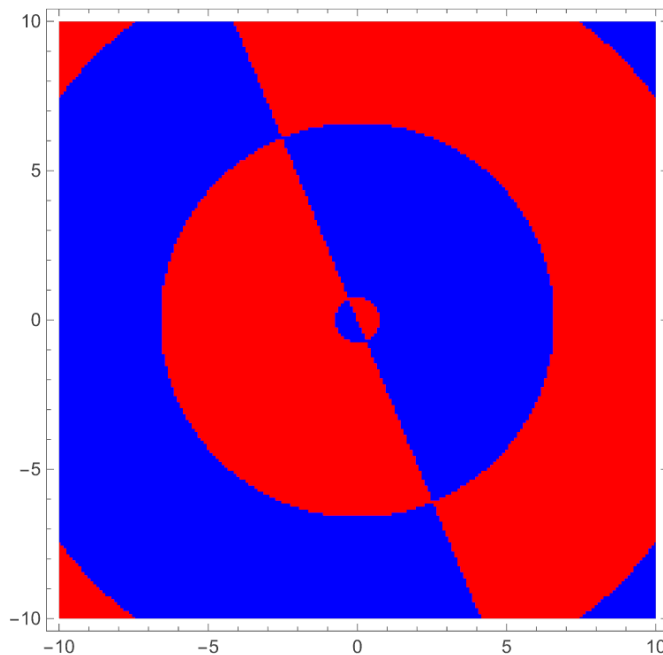
$$B = \frac{A_{\text{mag}}}{r^2} (\theta_r - \Gamma \theta_\phi) \times \left\{ 1 - 2H \left[\theta - \left(\frac{\pi}{2} + \theta_{\text{tilt}} \sin \left(\phi - \frac{r\Omega_\odot}{U_{\text{SW}}} \right) \right) \right] \right\}$$



Zero current sheet at given time for slow and fast solar wind conditions ([Jokipii and Thomas, 1981](#))

Presence of magnetic sectors I/II

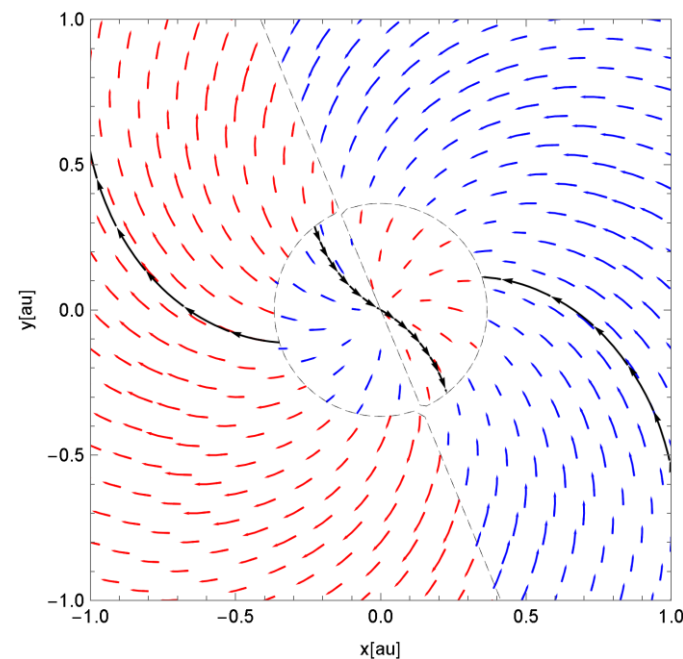
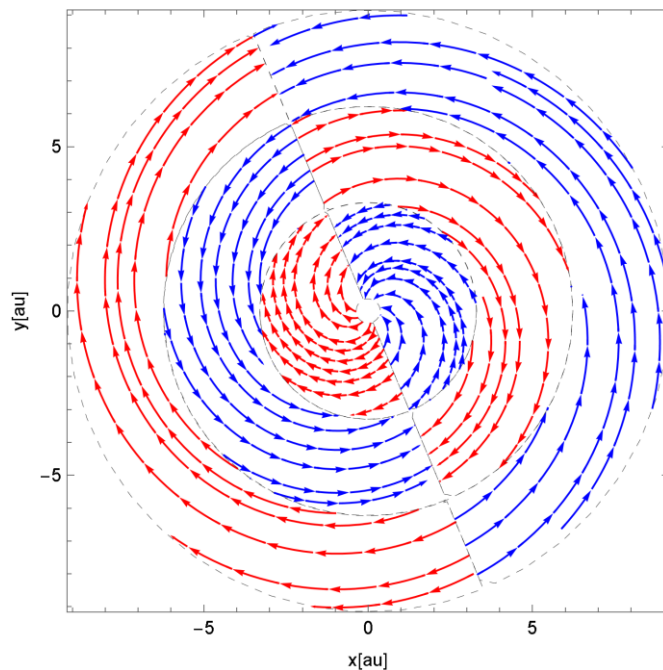
Sectors become more widely spaced as solar wind speed increases since magnetic field lines become more radial.



Sectorial structure of the IMF (inwards: blue, outwards: red) within the equatorial plane of the Sun for $U=800 \text{ km/s}$, vs. 200 km/s (right).

Presence of magnetic sectors II/II

As a consequence of the tilt between the magnetic and rotation axes of the sun a plane that intersects the wavy current sheet contains magnetic sectors.



Magnetic field lines (inwards: blue, outwards: red) within the equatorial plane of the sun for $U=400\text{km/s}$, and a tilt angle 5 degrees.

(Lindner Clara 2025)

Everything is time dependent!

Long-Term Trends (Decades to Centuries),
long-term solar magnetic evolution

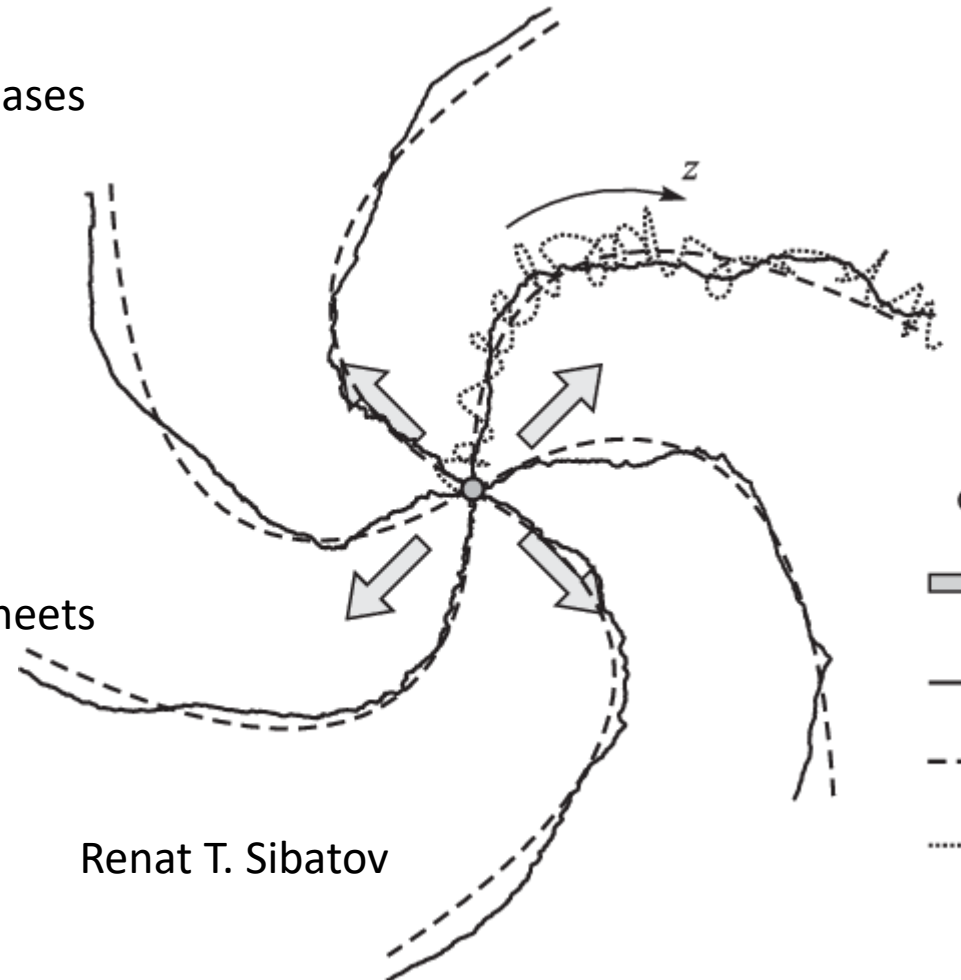
Solar Cycle (≈ 11 -Year Cycle)
polarity reversal, disordered vs. regular phases

Solar Rotation (≈ 27 -Day Period)
sectorial structure rotates

Transient Events (Minutes to Days)
coronal mass ejections, magnetic clouds

Short-Term Fluctuations (Seconds to Hours),
Alfven waves, turbulence, local current sheets

Planetary Interactions (Localized, Time-Variable)
magnetic reconnection



Averaged mathematical models

Classical (time dependent) Parker spiral model :

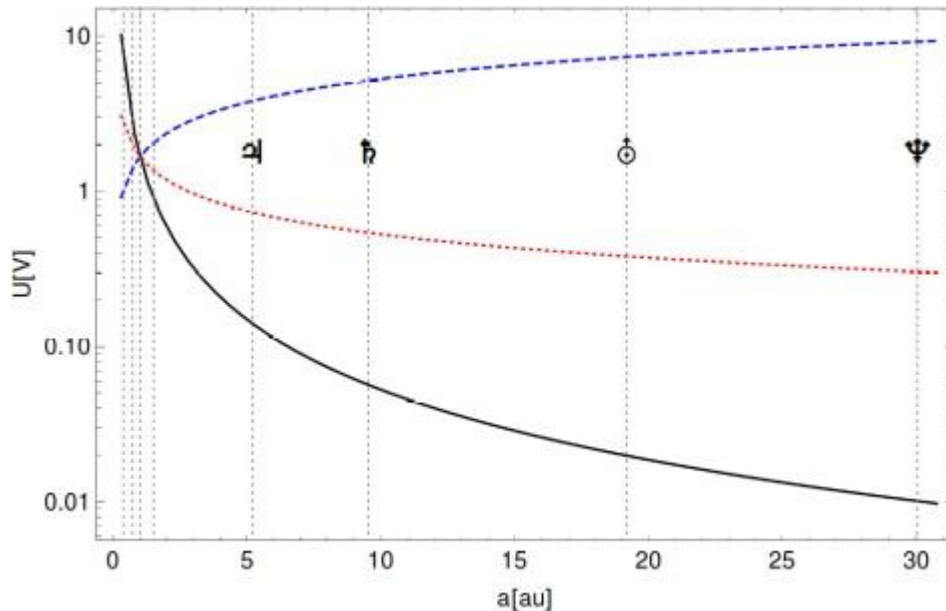
$$B_R = B_0 \left(\frac{r_0}{r} \right)^2 b_R(t) \quad b_R(t) = \cos(2\pi t/T + \varphi_0)$$

$$B_T = B_0 \left(\frac{r_0}{r} \right) b_T(t) \quad b_T(t) = \cos(\vartheta) \cos(2\pi t/T + \varphi_0)$$

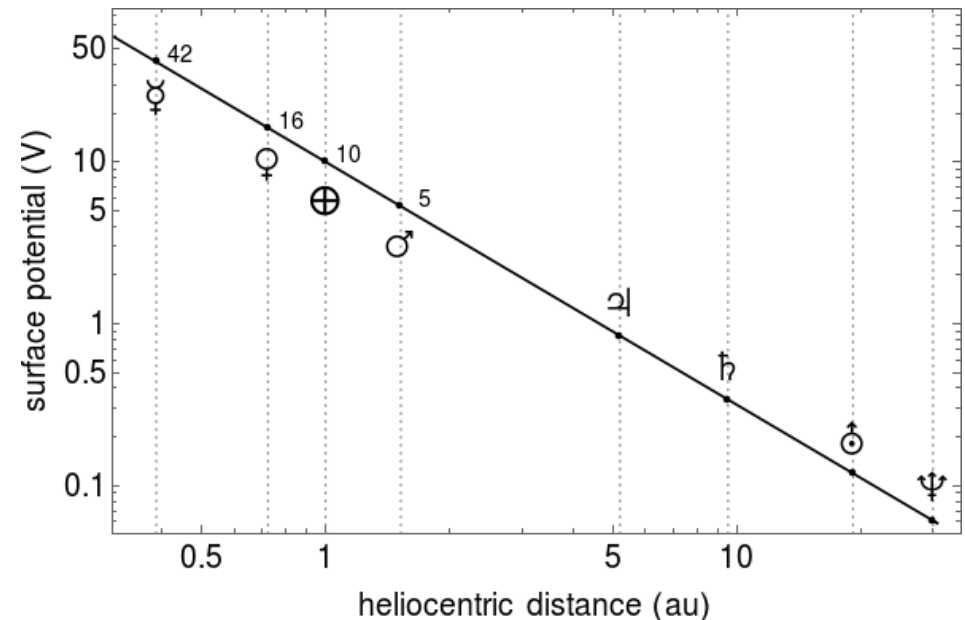
Importance of the normal component :

$$B_N = B_0 \left(\frac{r_0}{r} \right)^\kappa b_N(t) \quad b_N(t) = 1 + \cos(2\pi t/T)$$

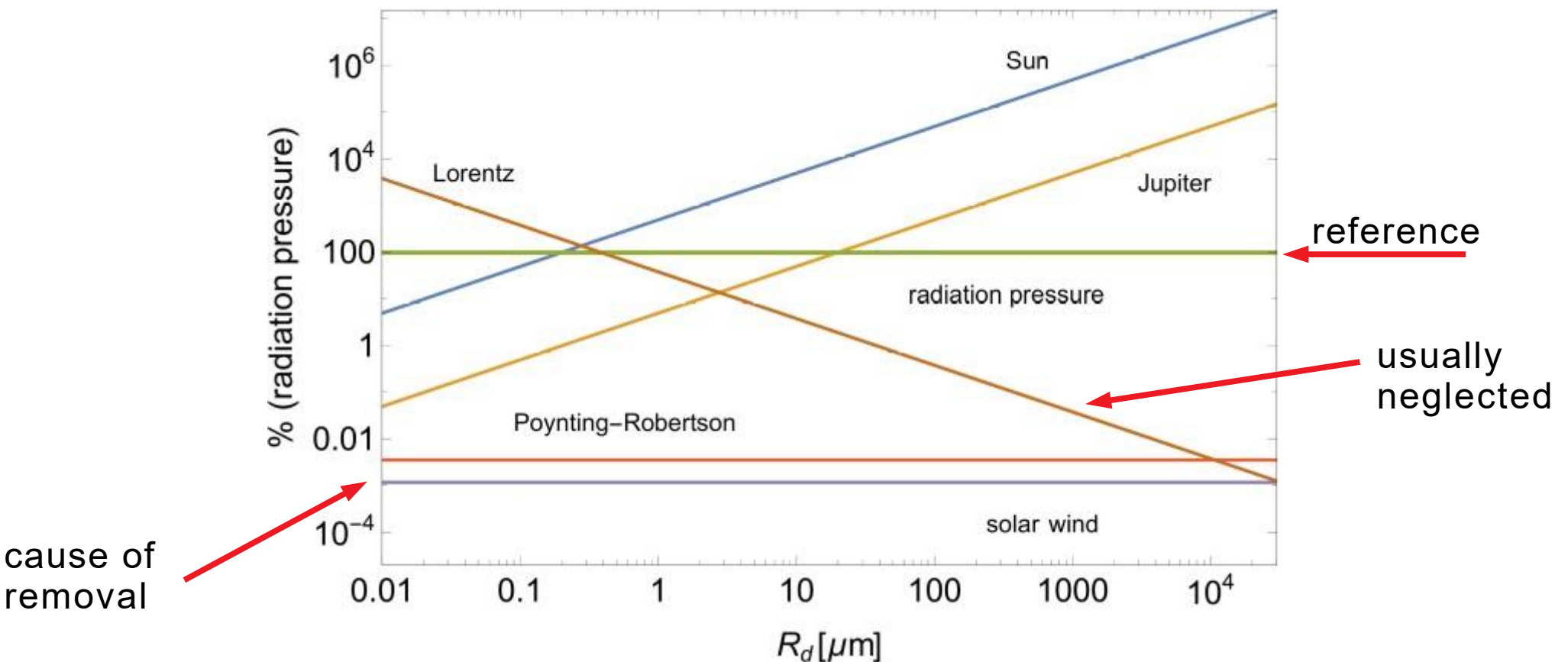
Study in distance for different κ (1=black, 2=red, 3=blue) :



- Mimics solar cycle with period T
- Radial component falls with $1/r^2$
- Tangential component falls with $1/r$
- Normal component falls with $1/r^\kappa$
- Non-zero mean of normal component



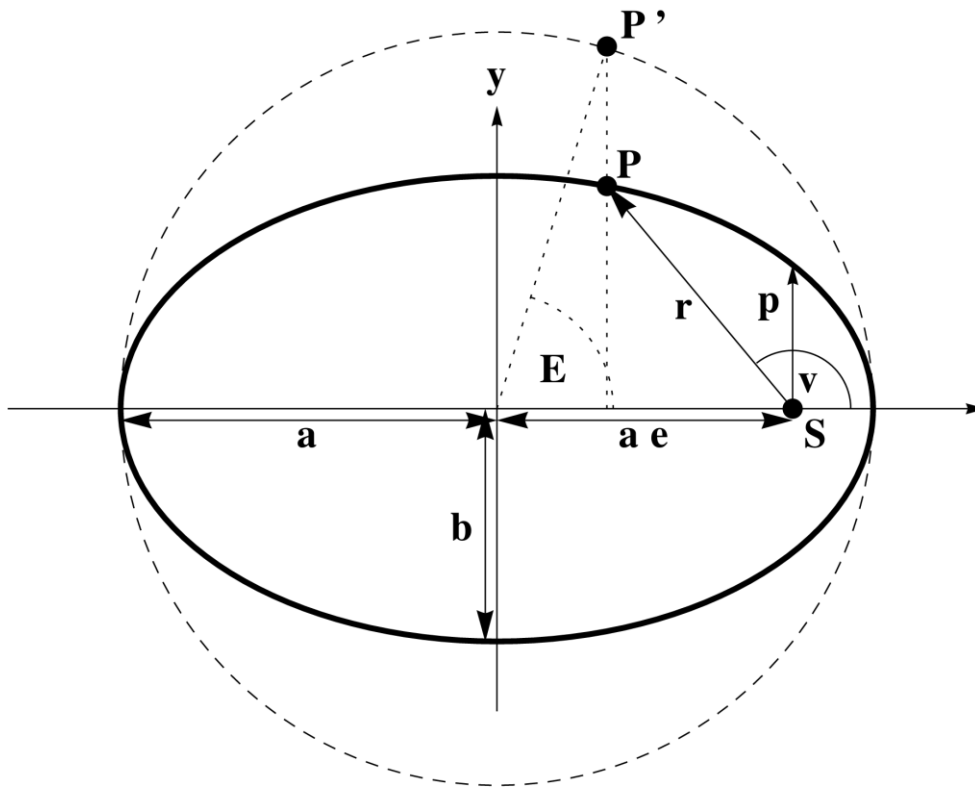
Forces, orbital motion



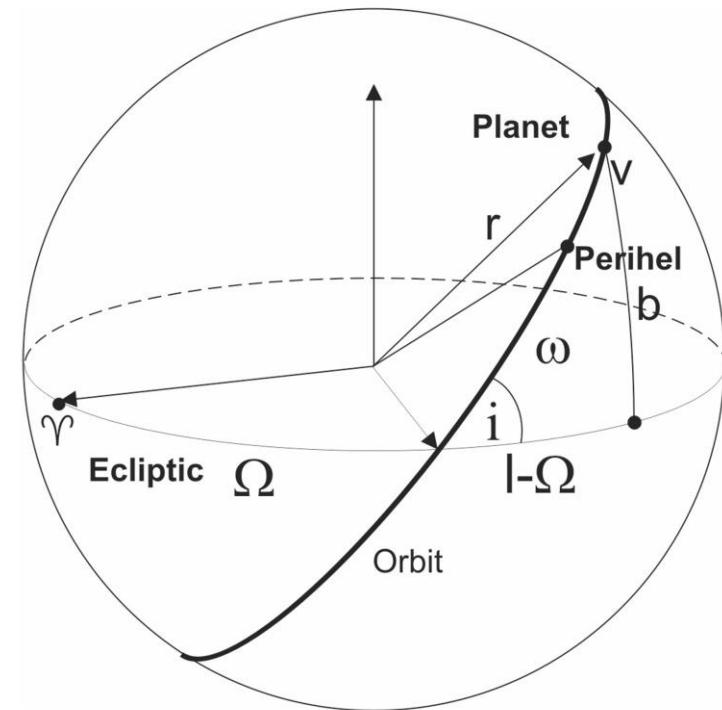
Force magnitudes evaluated for dust grains with 2.8 gcm^{-3} density at a distance of 8AU from the sun (depends on distance etc..)

Orbital elements

2D

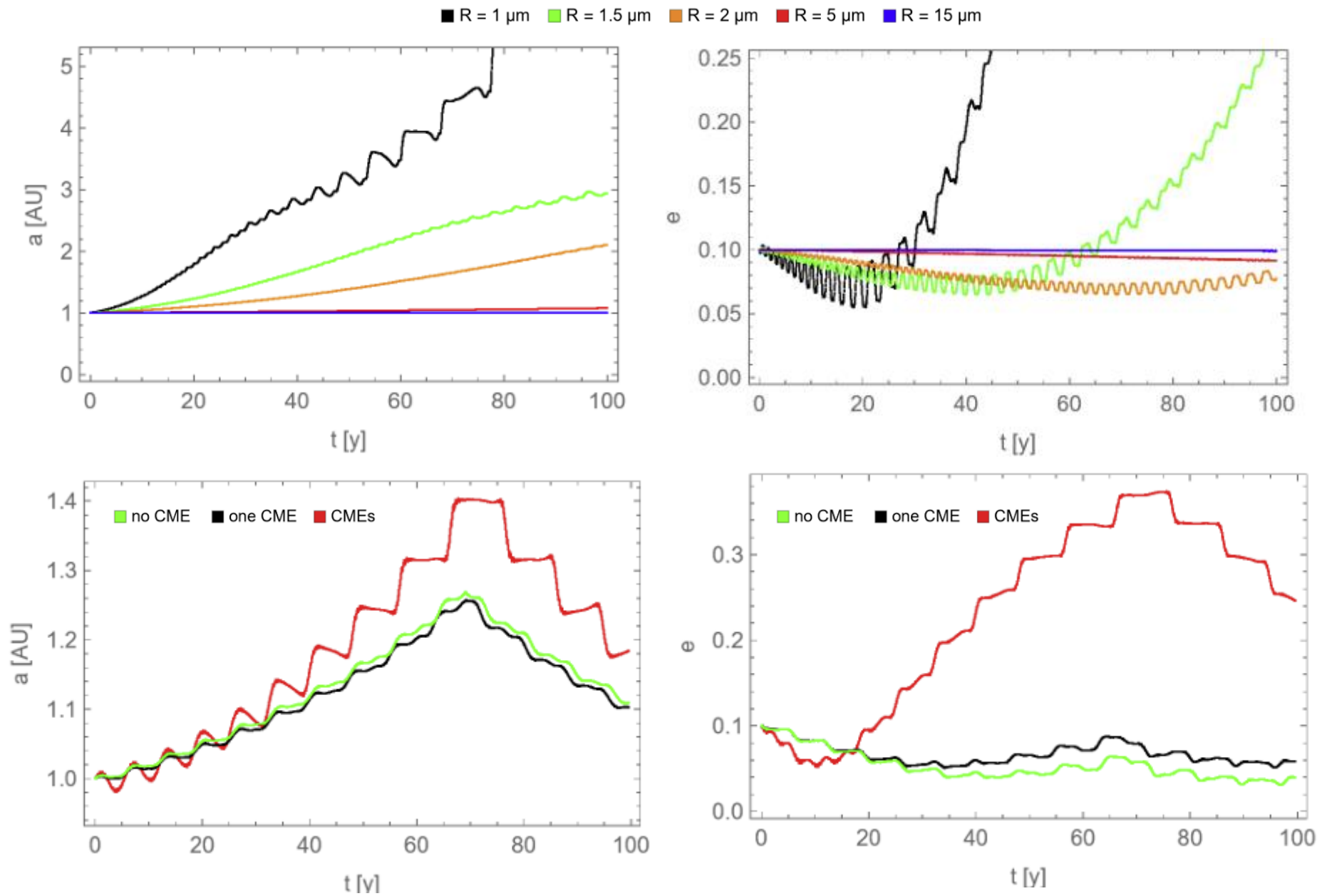


3D



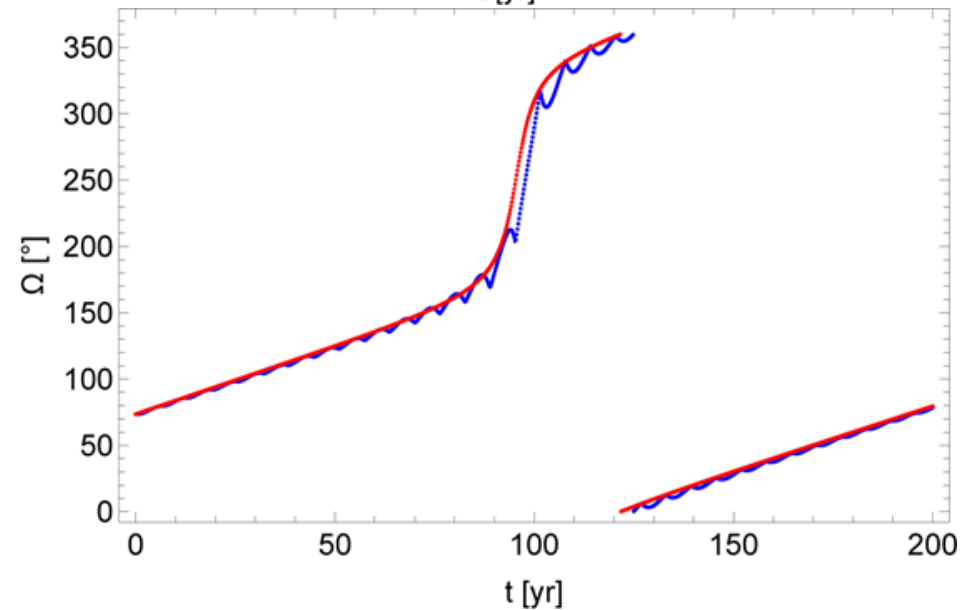
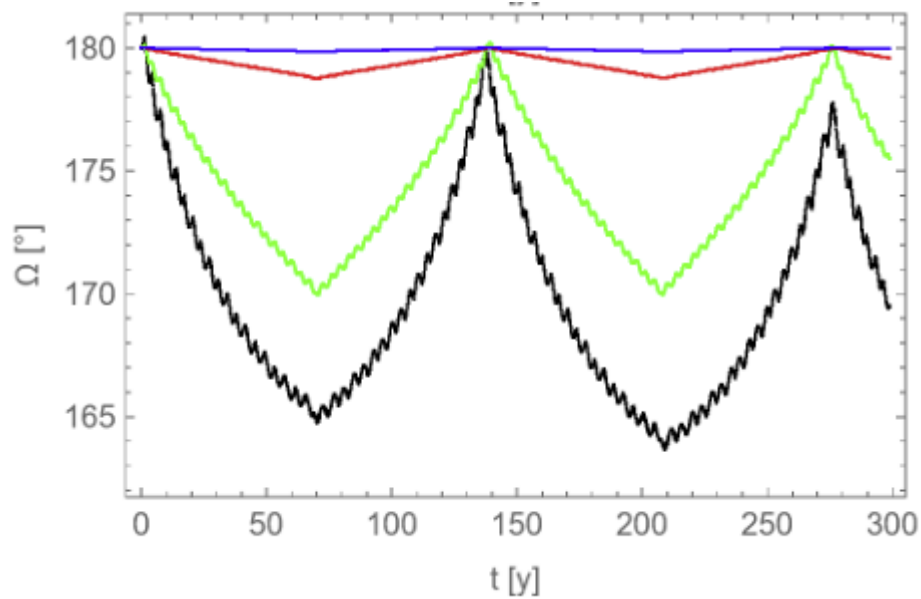
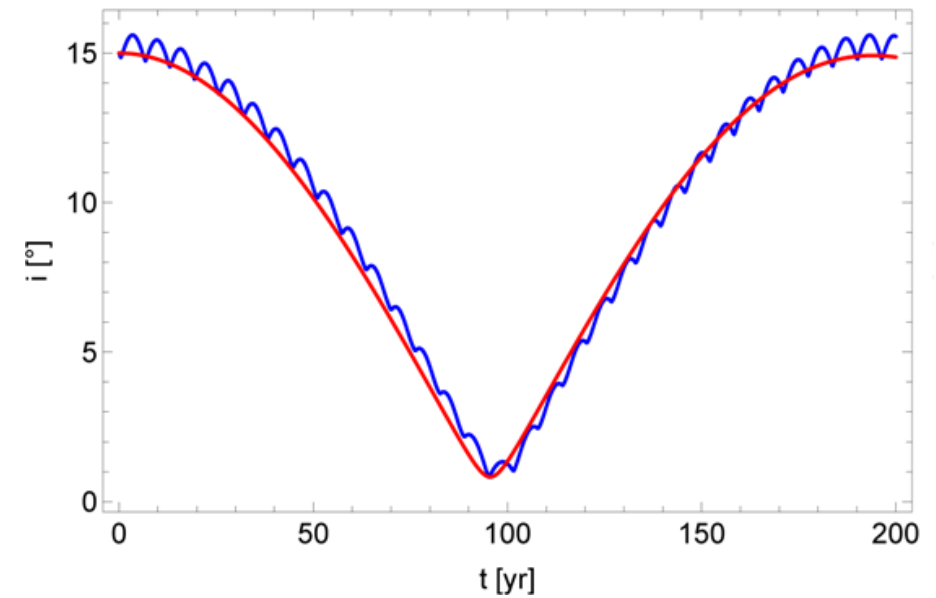
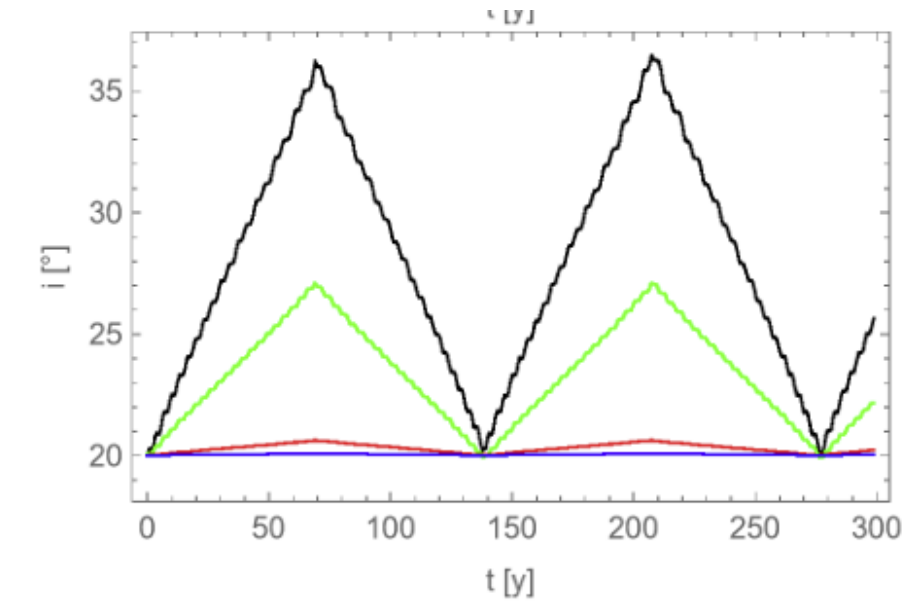
Radius r , true anomaly v , semi-major axis a , eccentricity e , perihel ω , ascending node longitude Ω , mean anomaly M

Dynamical effects on radial distance



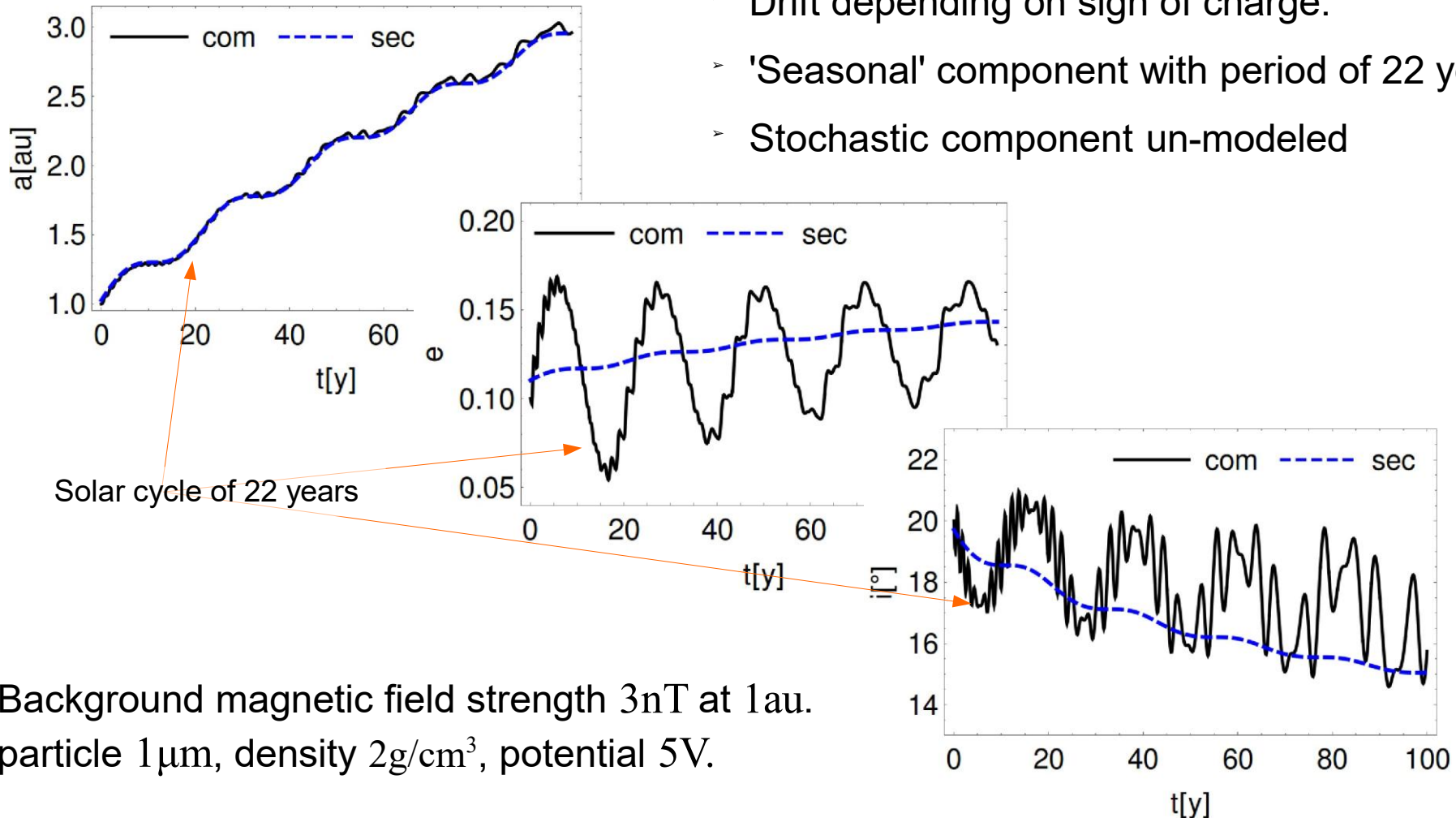
Latitudinal (spatial) dynamics

■ $R = 1 \mu\text{m}$ ■ $R = 1.5 \mu\text{m}$ ■ $R = 2 \mu\text{m}$ ■ $R = 5 \mu\text{m}$ ■ $R = 15 \mu\text{m}$



Secular dynamics I/II

- Drift depending on sign of charge.
- 'Seasonal' component with period of 22 years
- Stochastic component un-modeled

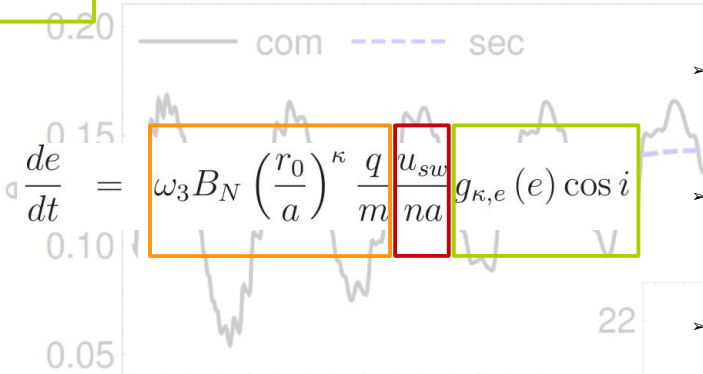
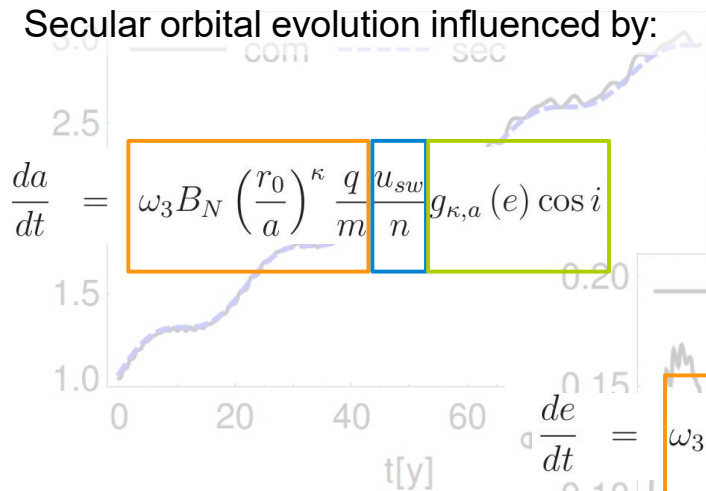


Lhotka, Bourdin, Yasuhito (2016)

Secular dynamics II/II

Secular orbital evolution influenced by:

- › Deviation between magnetic axis and rotation axis : ω_3
- › Norm of the normal magnetic field component : B_N
- › Reciprocal of semi-major axis : $1/a^\kappa$



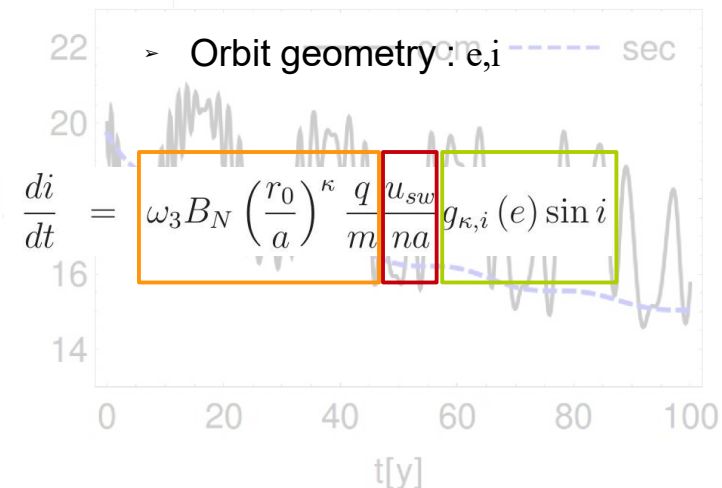
- › Charge over mass ratio: q/m (sign!)
- › Ratio of solar wind speed over mean motion u_{sw}/n

$$\omega_3 B_N \left(\frac{r_0}{a} \right)^\kappa \frac{q}{m}$$

- › Common proportionality factor defines maximum strength and sign of secular drift

$$\frac{u_{sw}}{n} \text{ vs. } \frac{u_{sw}}{na}$$

- › Additional $1/a$ factor decreases effect for eccentricity and inclination
- › Secular effects decrease / increase for increasing inclination



- › Orbit geometry : e, i

Lhotka, Bourdin, Yasuhito (2016)

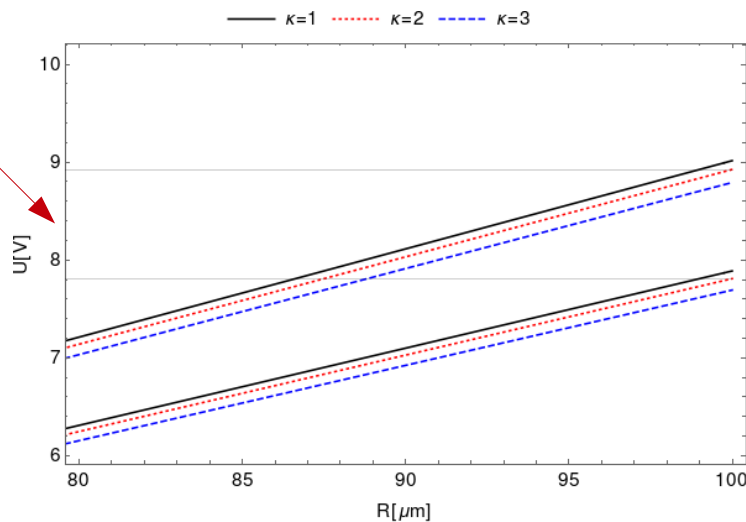
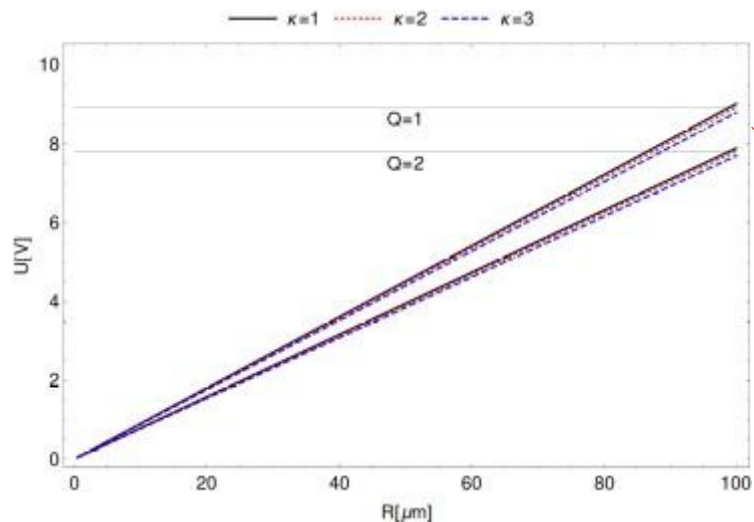
Balanced (stable) solutions

Dependency on solar wind conditions
normal magnetic field strength
solar radiation pressure

- Inverse proportional to mean solar wind speed
- Inverse proportional to mean normal interplanetary magnetic field component
- Direct proportional to ratio of solar radiation pressure of gravitational attraction of the Sun

$$\frac{q}{m} = \frac{\beta}{c} \frac{(Q + \eta) n^3 a^{\kappa+2} G_{\kappa}(e)}{Q r_0^{\kappa} \cos(i)} (B_N u_{sw} \omega_3)^{-1}$$

Dependency on optical parameters :



Different IMF models

Different optical and physical properties

Dependency on physical parameters :

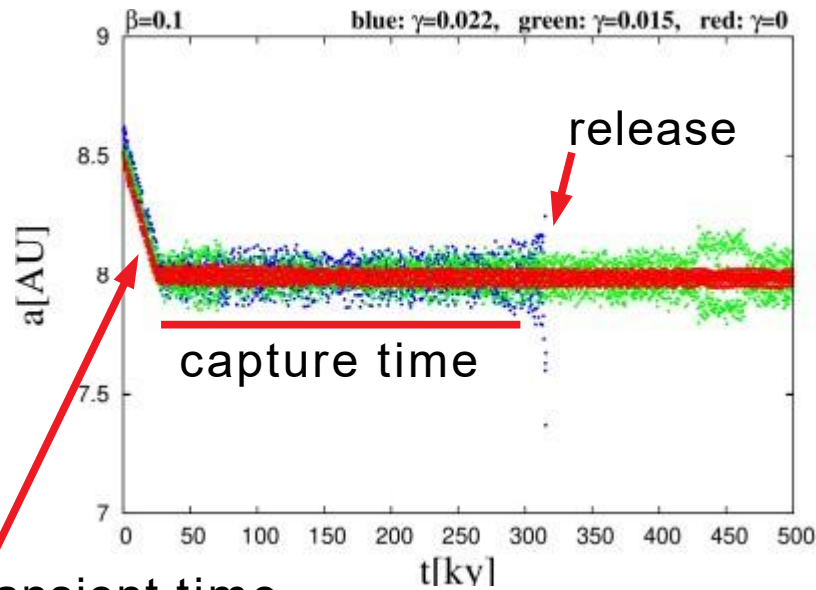
- Depends on optical efficiency factor Q (incoming vs. outgoing vs. absorbed energy in photon – particle interaction)
- Depends on particle size and density of the dust grain
- Charging mechanisms, stability of charge equilibrium

Resonant capture I/III

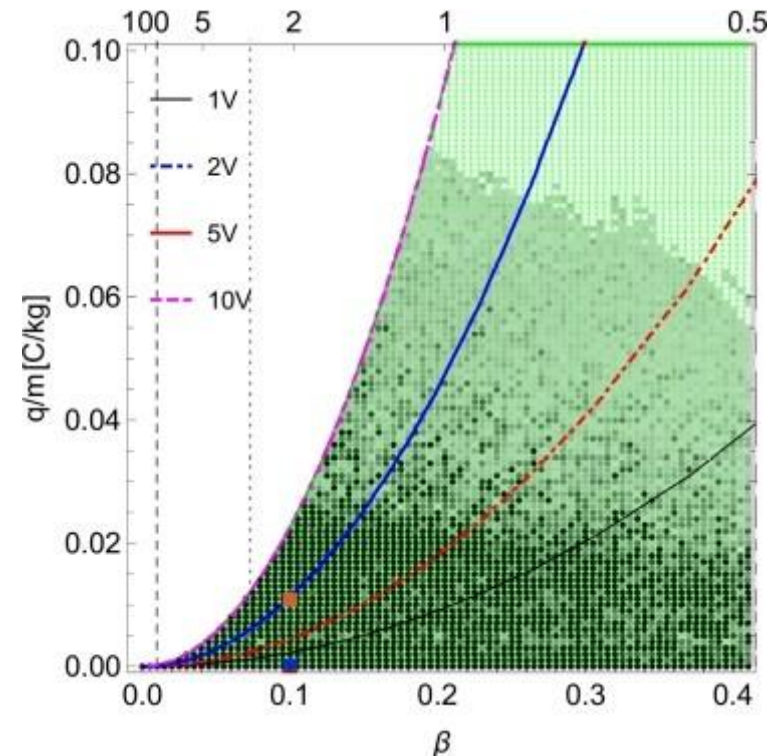
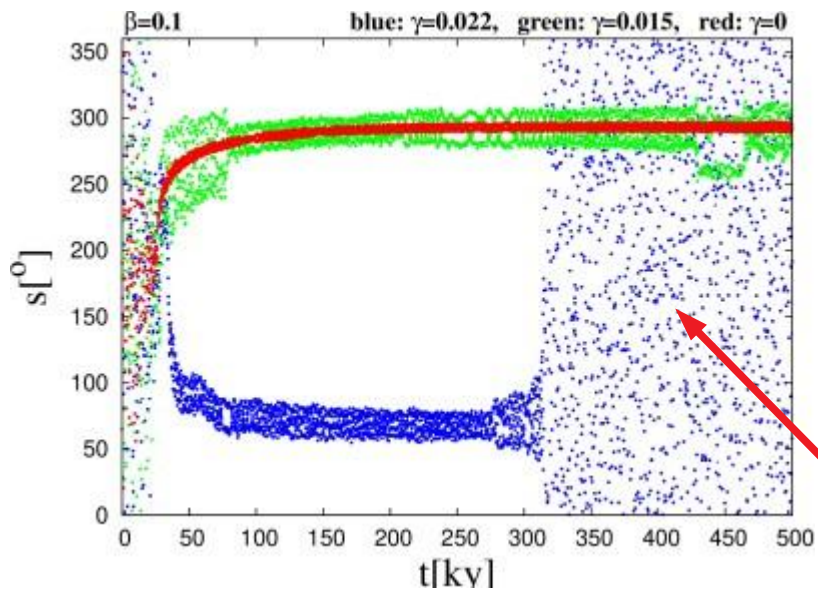
Color code :

Lhotka & Gales 2019

- red = uncharged
- green = slightly charged
- blue = higher charge



Transient time

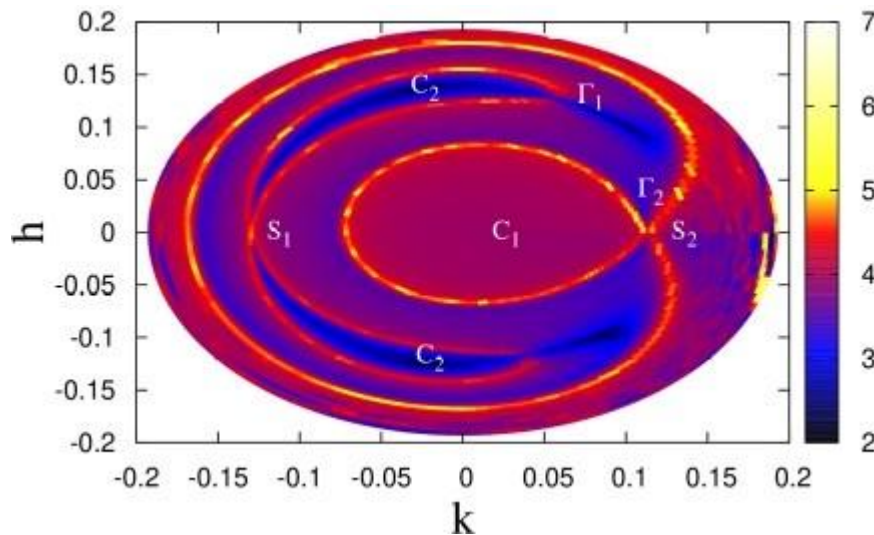


Resonant capture II/III

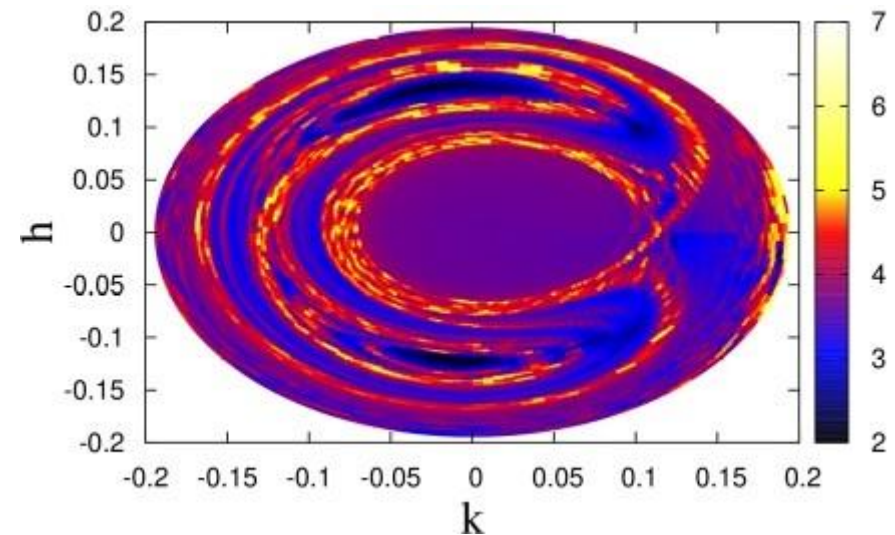
resonant argument: $qs = (p + q)\lambda_1 - p\lambda + q\bar{\omega}$

Lhotka & Gales 2019

Gravitational problem :



Gravity + Lorentz force



S_1, S_2 : saddles of the resonance

Γ_1, Γ_2 : separatrices

C_1, C_2 : bounded regions

$$(k, h) = (e \cos(s), e \sin(s))$$

eccentricity

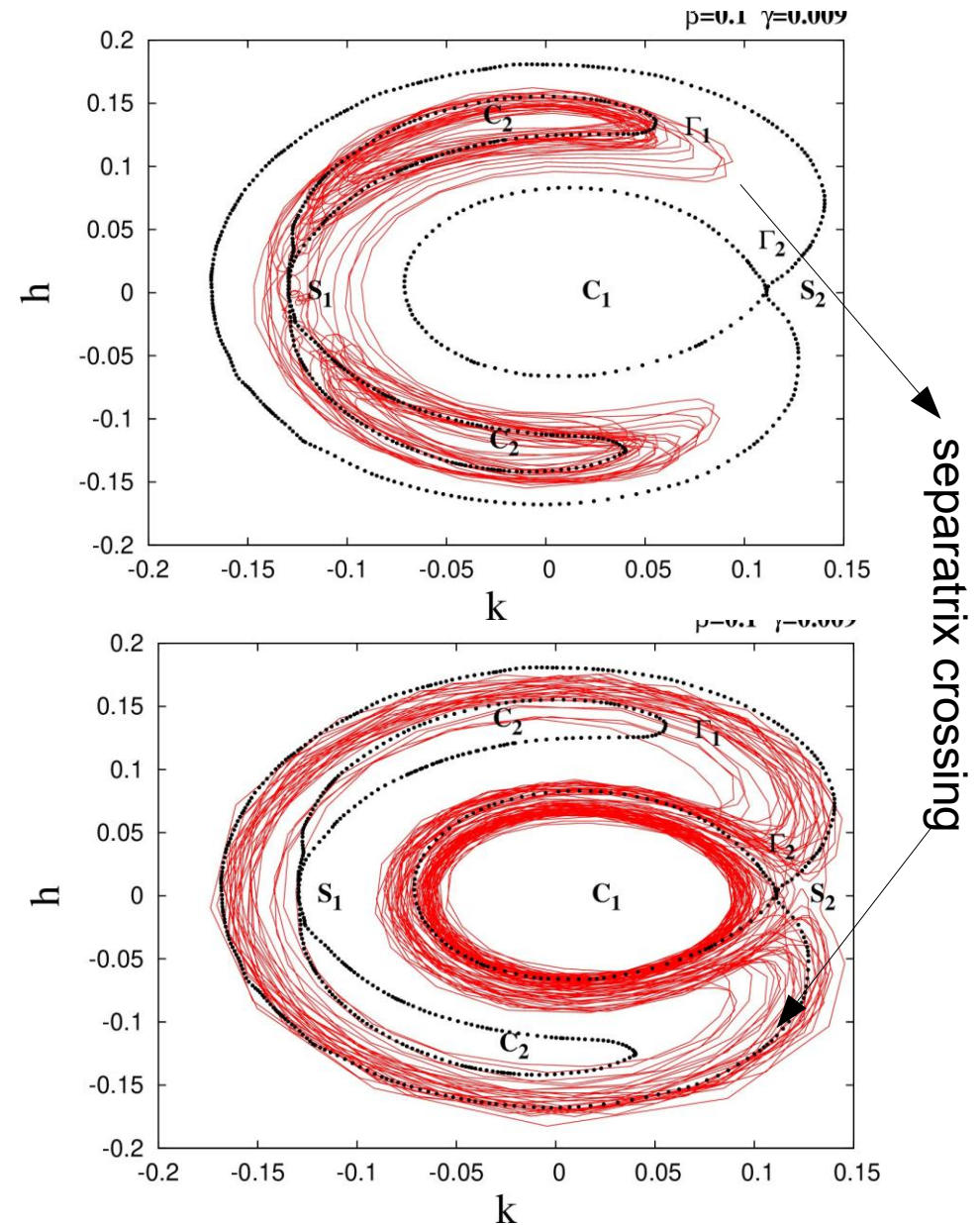
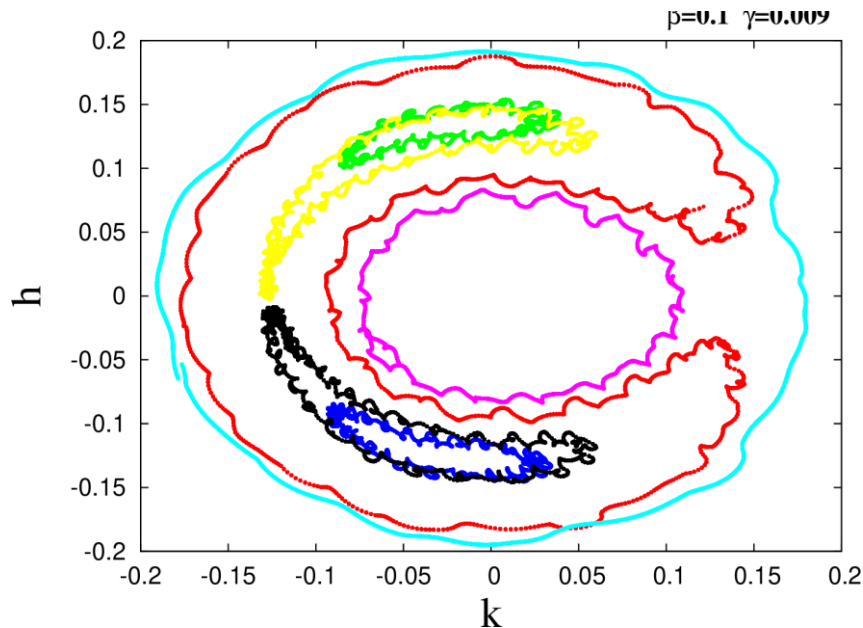
resonant argument:

Charge 'blurs' widths of separatrix curves.

Resonant capture III/III

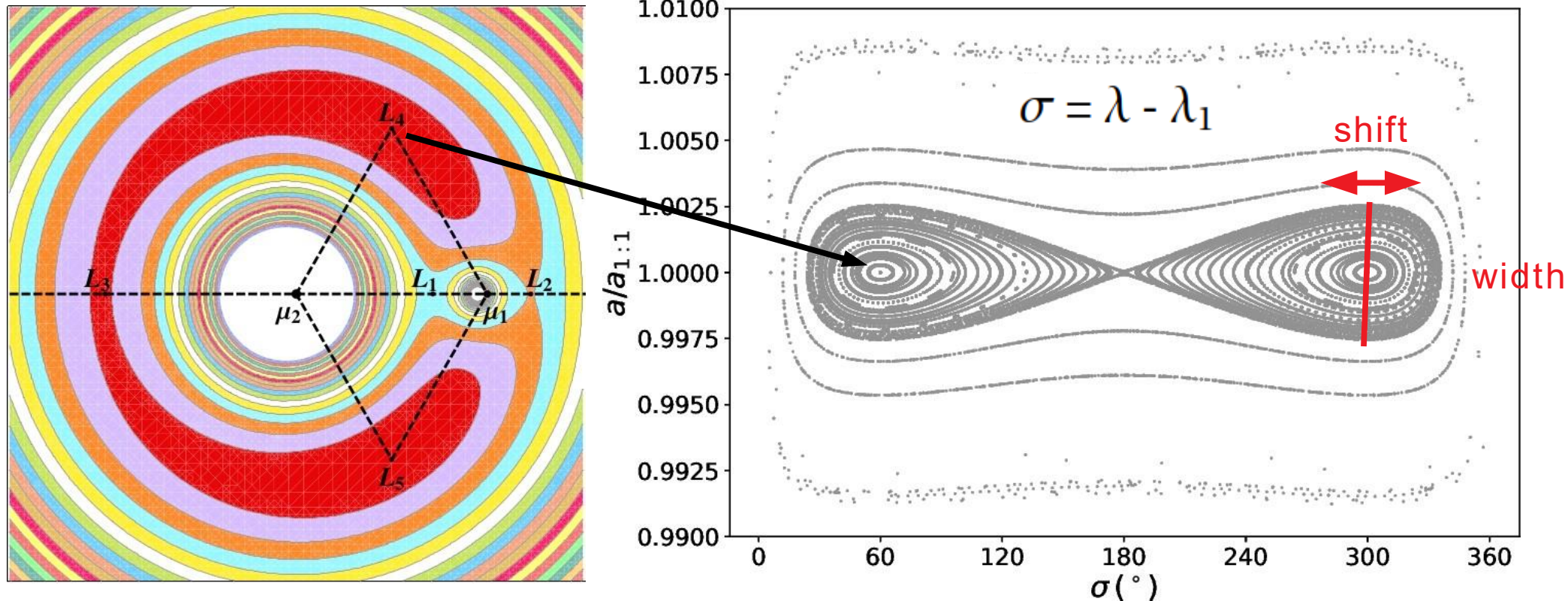
On short time scales motion is trapped in specific regions:

- librational motion :
red, green (tadpole type)
yellow, black (horseshoe type)
- rotational motion :
magenta (small eccentricities)
cyan (large eccentricities)



Co-orbital motions

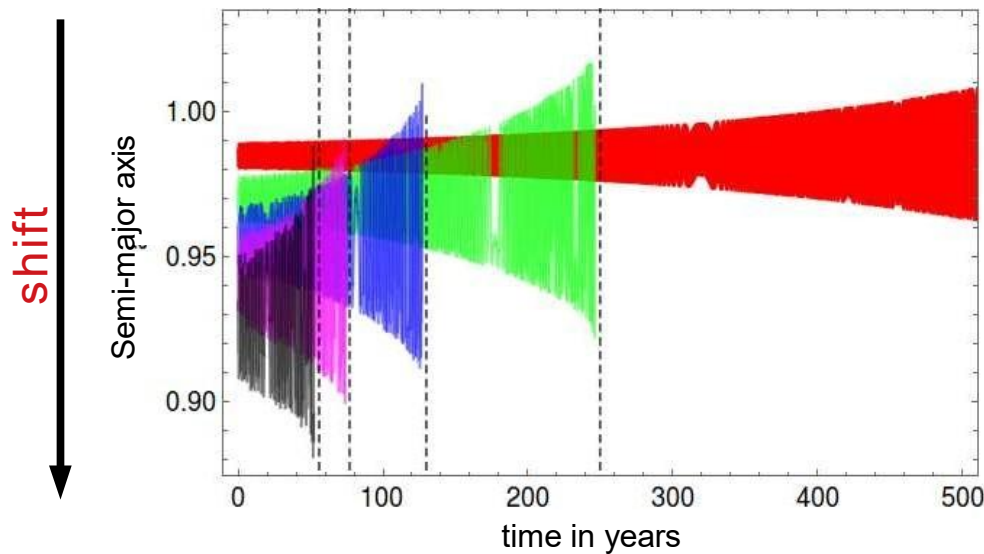
Dvorak, Lhotka 2013



- Lagrange problem: 1:1 MMR between planet (Jupiter, Venus, etc...) and dust particle.
- Particles near L_4, L_5 experience temporary capture
- Strong influence of non-gravitational forces on location / resonance width / capture times

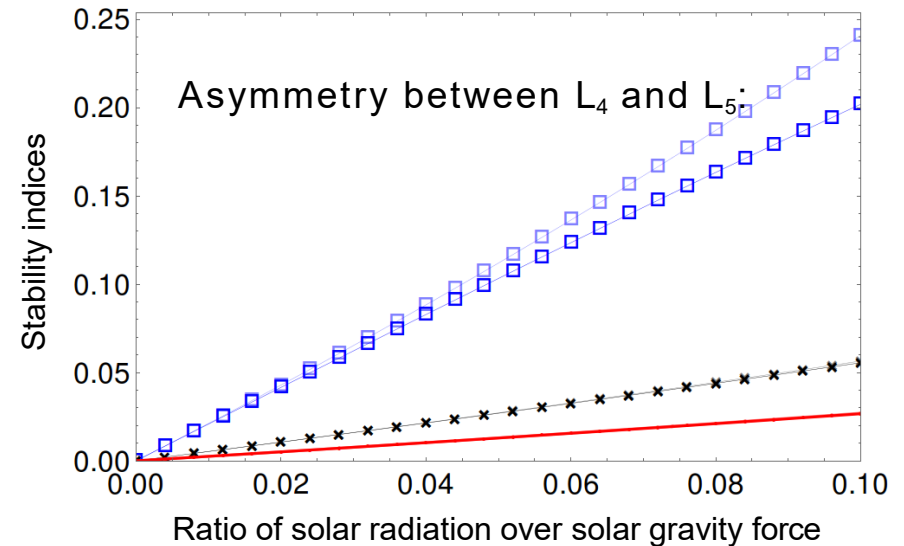
Shift of equilibria I/II

Poynting-Robertson effect and solar wind drag on resonant motion close to L_4 (1:1):



Temporary capture for different size-to-mass ratios between primary and secondary

The higher the size-to-mass ratio the shorter the time of temporary capture.



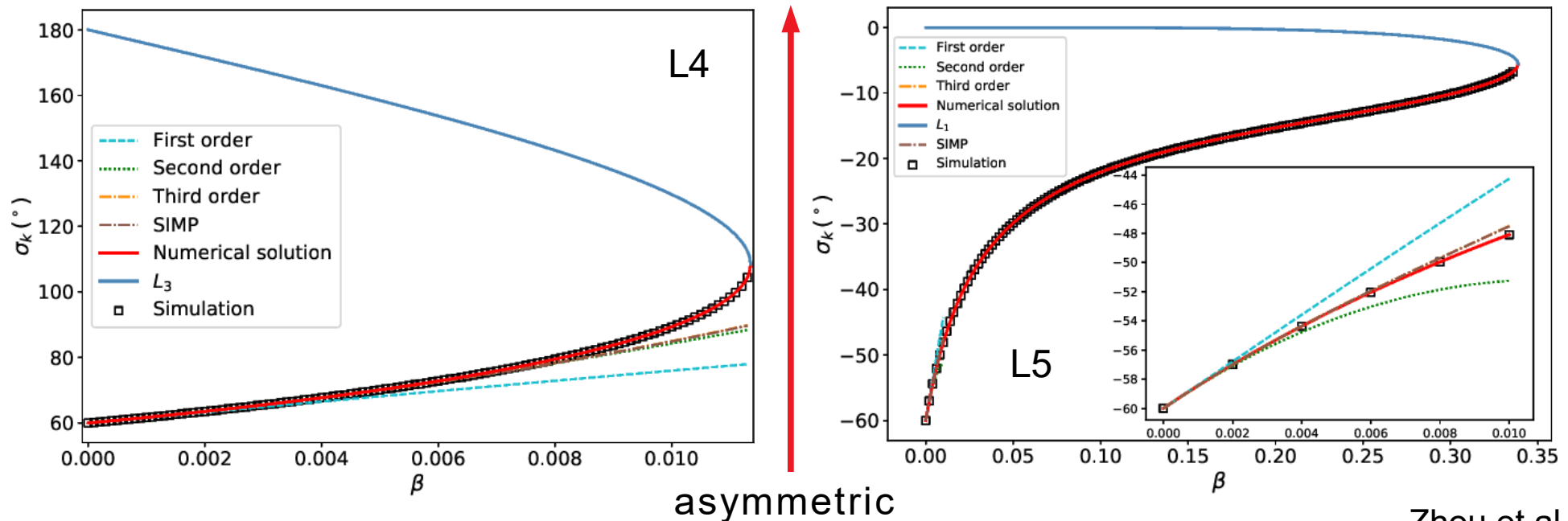
Analysis of stability indices reveal instability of motion close to resonance.

Depending on the physical parameters solar wind induces an asymmetry of the symmetric problem in the pure gravitational case.

Lhotka & Celletti 2015

Shift of equilibria II/II

Influence of non-gravitational forces on location of exact resonance condition



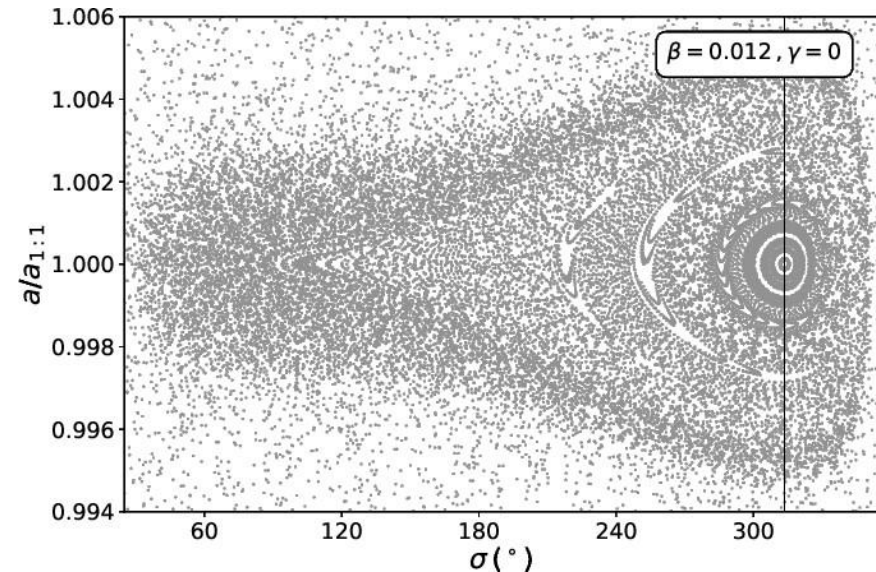
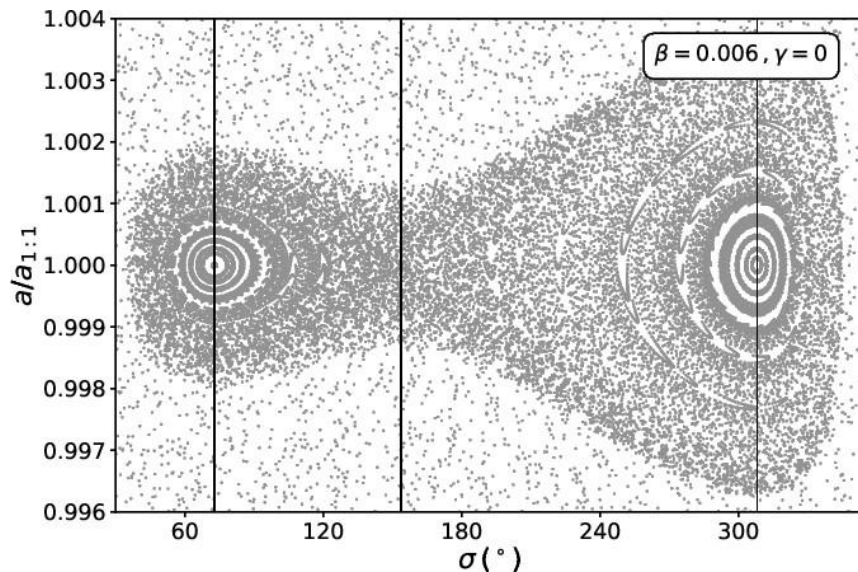
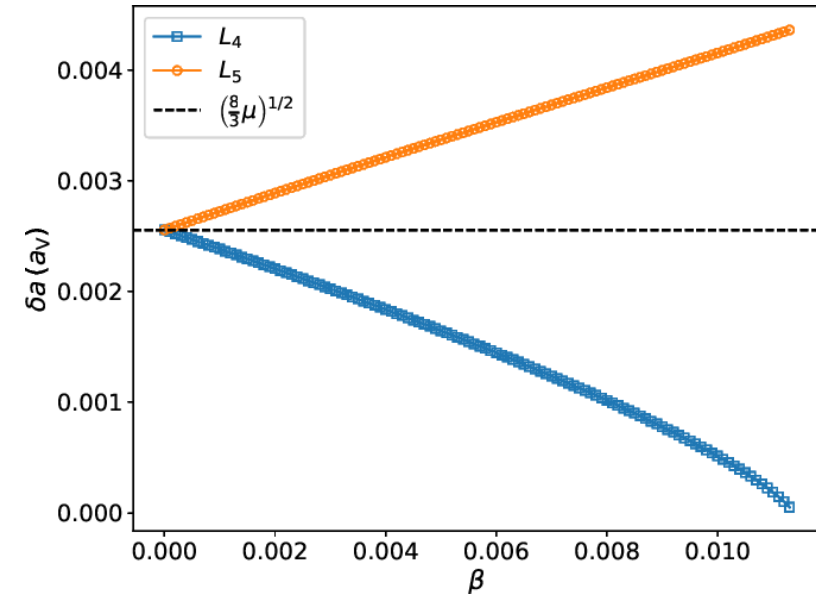
Zhou et al. 2021

- Asymmetry is caused by Poynting-Robertson effect and solar wind drag
- Strong dependency on size and composition (parameter beta)
- Does not only affect location of equilibria – but also resonance widths...

Extent of resonance widths

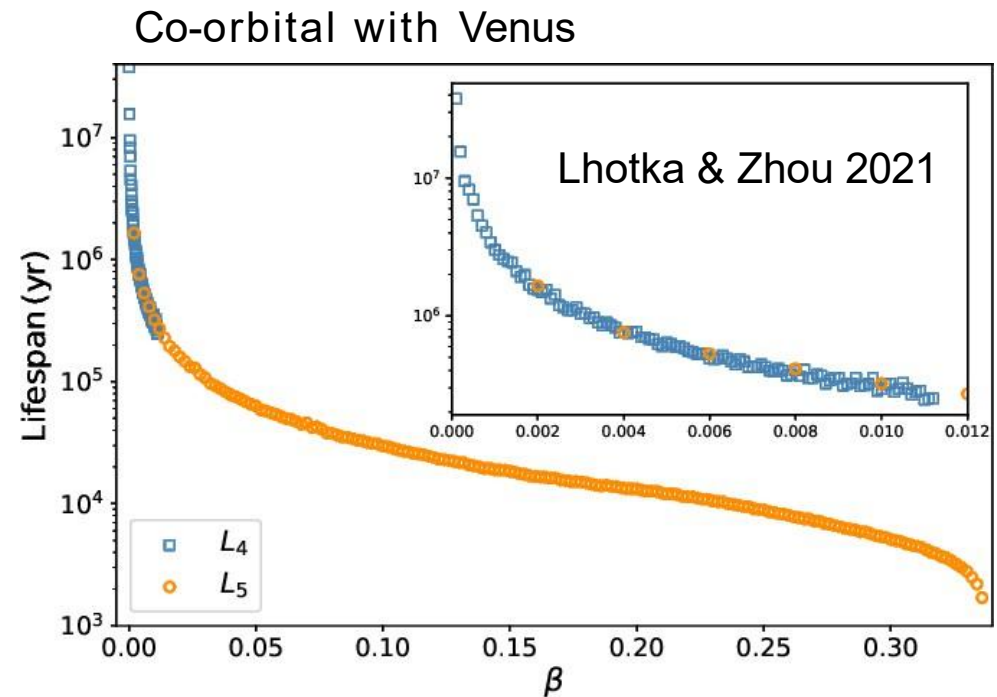
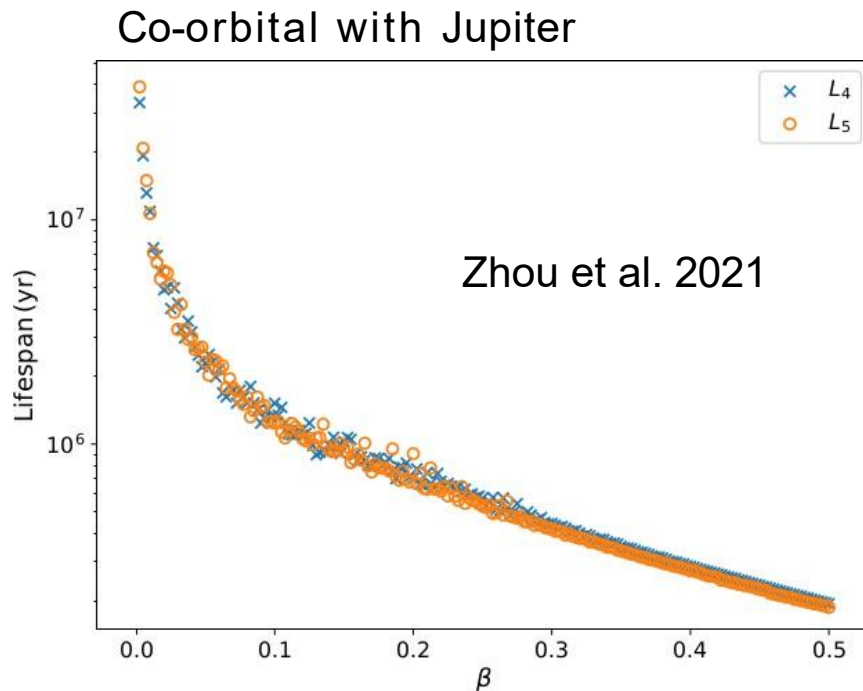
Non-gravitational forces play a crucial role in the extent of the resonance widths:

- Strong dependence on particle radii
- Symmetry between L4 and L5 is broken for micron sized dust grains
- Probability of temporary trapping close to L4 smaller compared to L5



Temporary capture times

Capture times for dust grains are different in the inner / outer solar system.

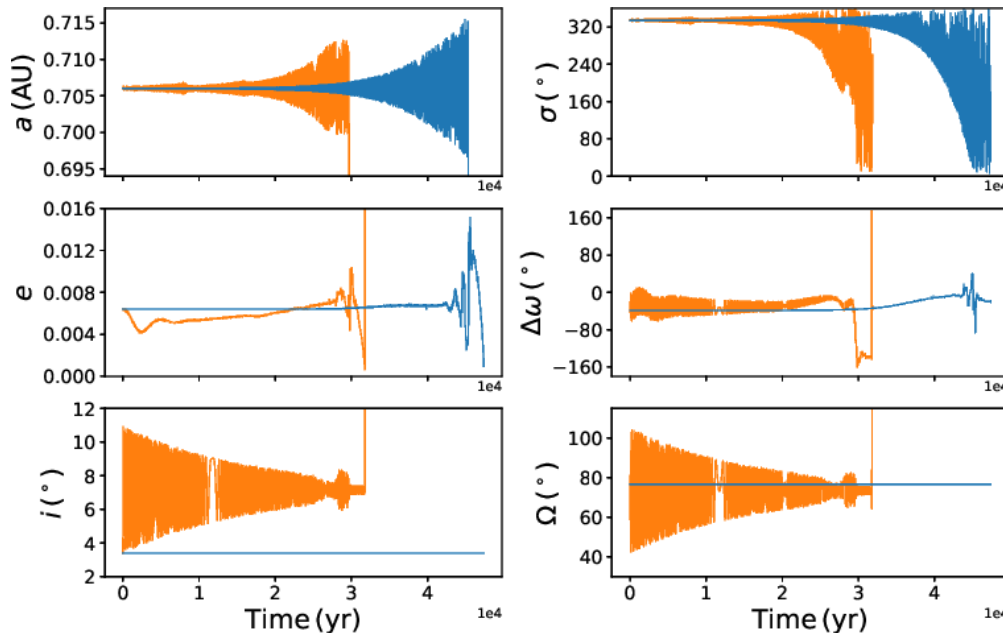


Structure of the curves depends on:

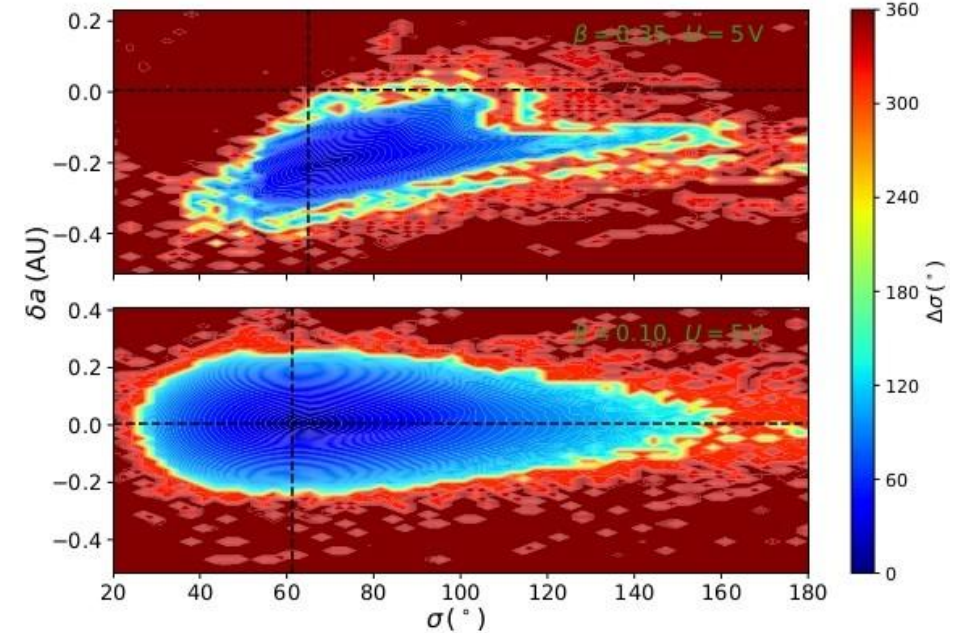
- distance from the sun (inner vs. outer solar system)
- particle size (radius, size-to-mass ratio)
- mass of the co-orbital planet (Venus vs. Jupiter)

Specific role of charge I/III

- Release from resonant locking occurs on shorter time scales.
- The resonant regions get distorted and shifted due to the interaction with the interplanetary magnetic field.



Reduced capture times: temporary capture of uncharged (blue) and charged (orange) particles.

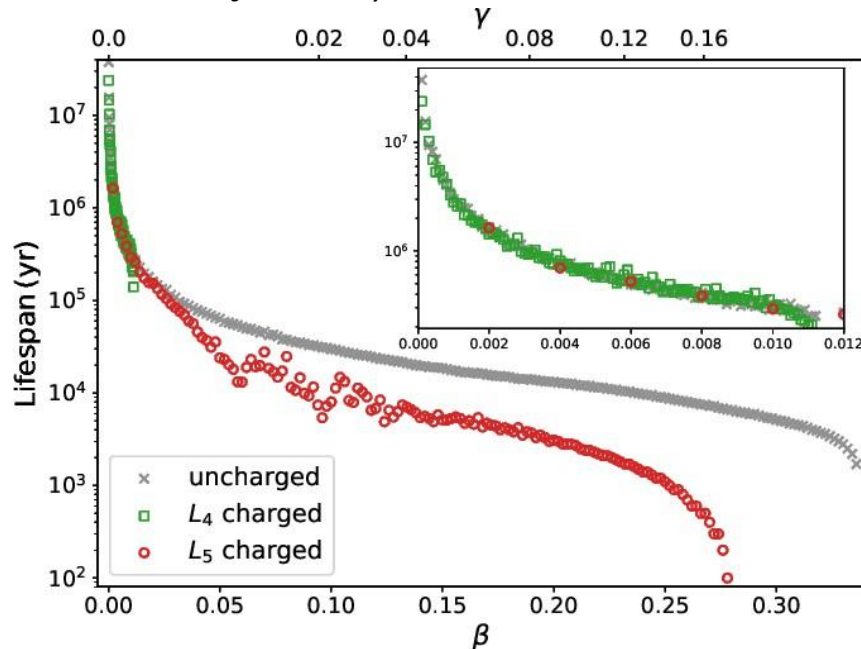


Libration amplitudes around resonant values in presence of charge.

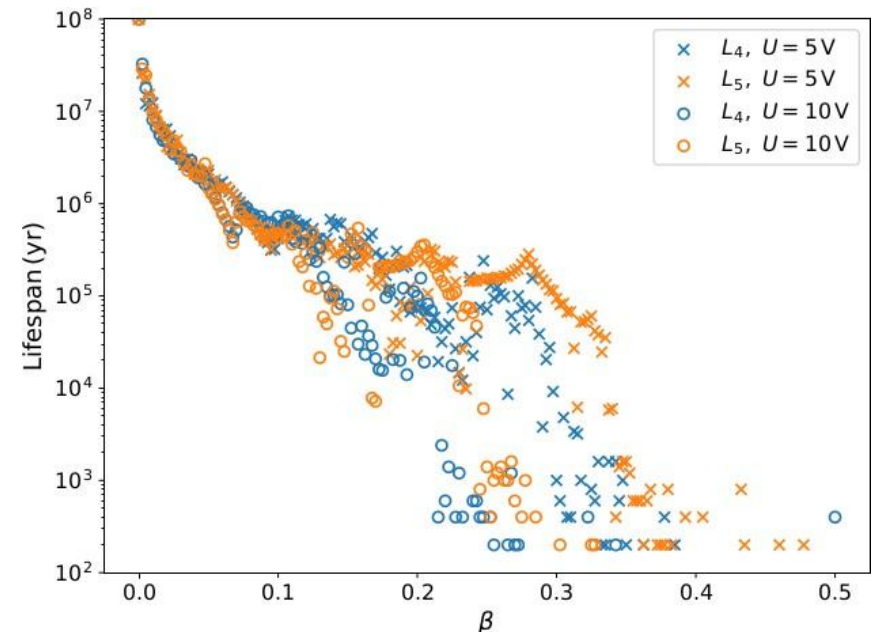
Lhotka & Zhou 2021

Specific role of charge II/III

Capture in resonant lock in mean motions with planet Jupiter (outer solar system).



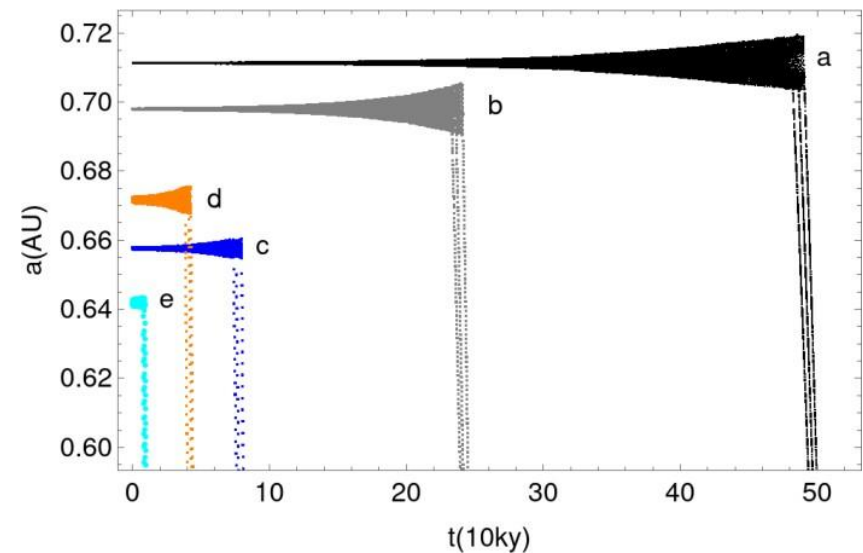
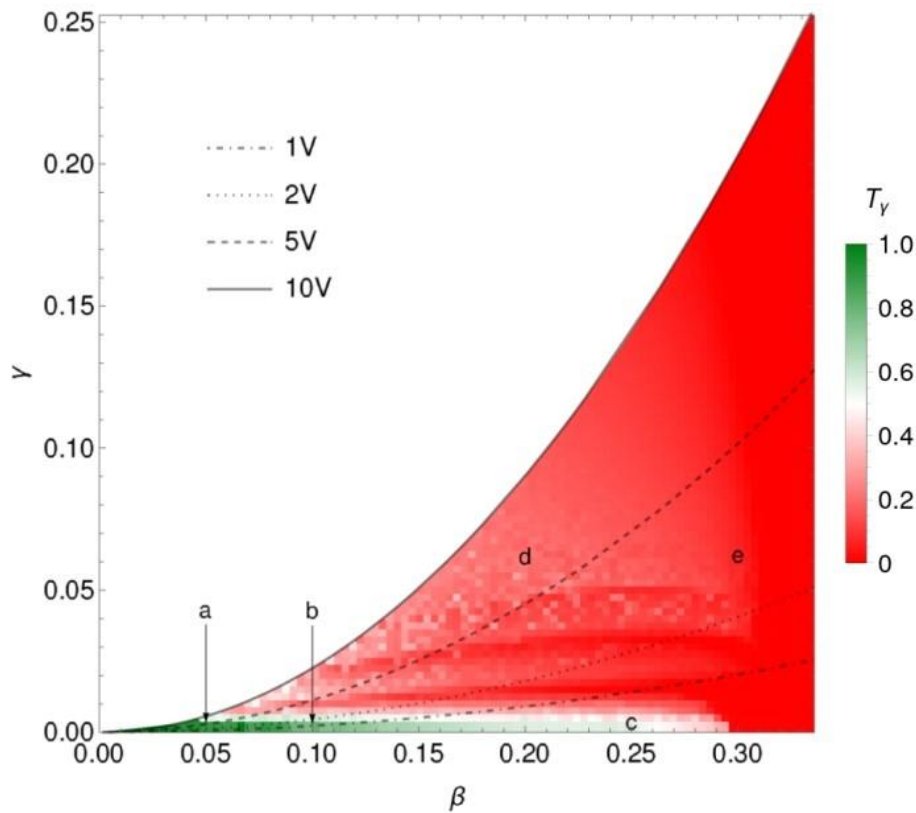
Capture in resonant lock in mean motions with planet Venus (inner solar system).



- Dependence on size (inverse to parameter beta) and charge-to-mass ratio (proportional to parameter gamma).
- Capture times also depend on mass of co-orbital planet (Jupiter vs. Venus) and distance from the sun.

Specific role of charge III/III

- Particle motion determined by interplay of radiation due to the sun and heliospheric magnetic field.
- Larger size-to-mass and charge-to-mass ratios experience stronger non-gravitational perturbations
- Physical parameters (radius, density, etc..) of particles determine orbital lifetimes close to resonance.

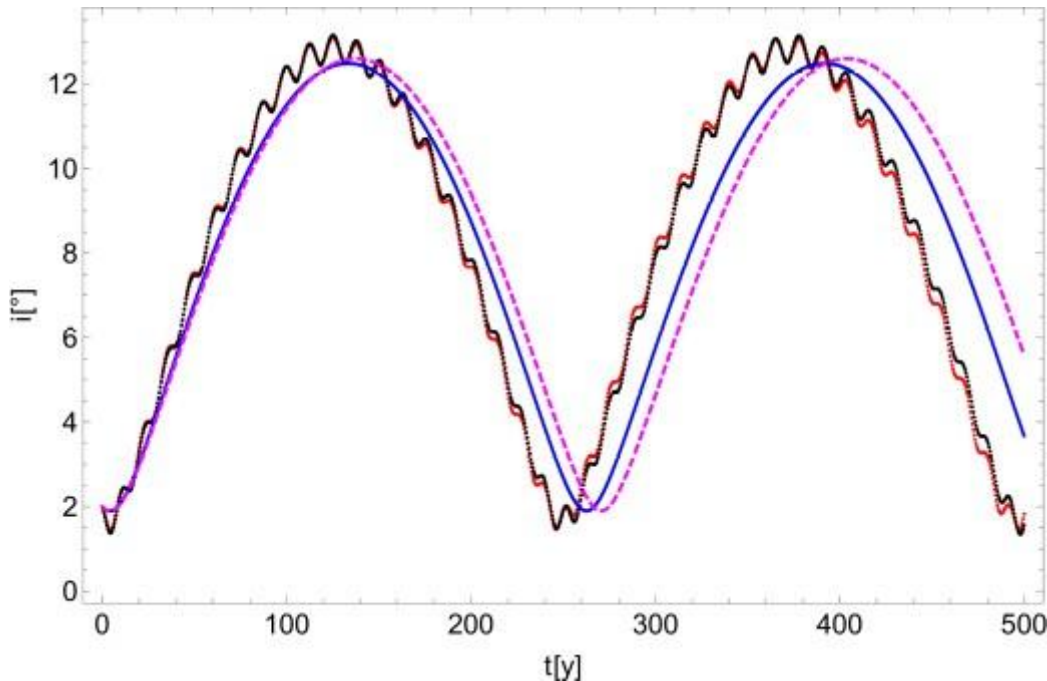


Zhou et al. 2021

Latitudinal variations

Numerical vs. analytical models

Lhotka & Gales 2019



inclination sun's rotation period

$$\Omega(t) = \left(\cos(i) \frac{\Omega_s}{n} - 1 \right) \Gamma t + \Omega(0)$$

background

$$\Gamma = \alpha \frac{q}{m} \frac{B_0}{2} \left(\frac{r_0}{a} \right)^2$$

charge-to-mass ratio

semi-major axis

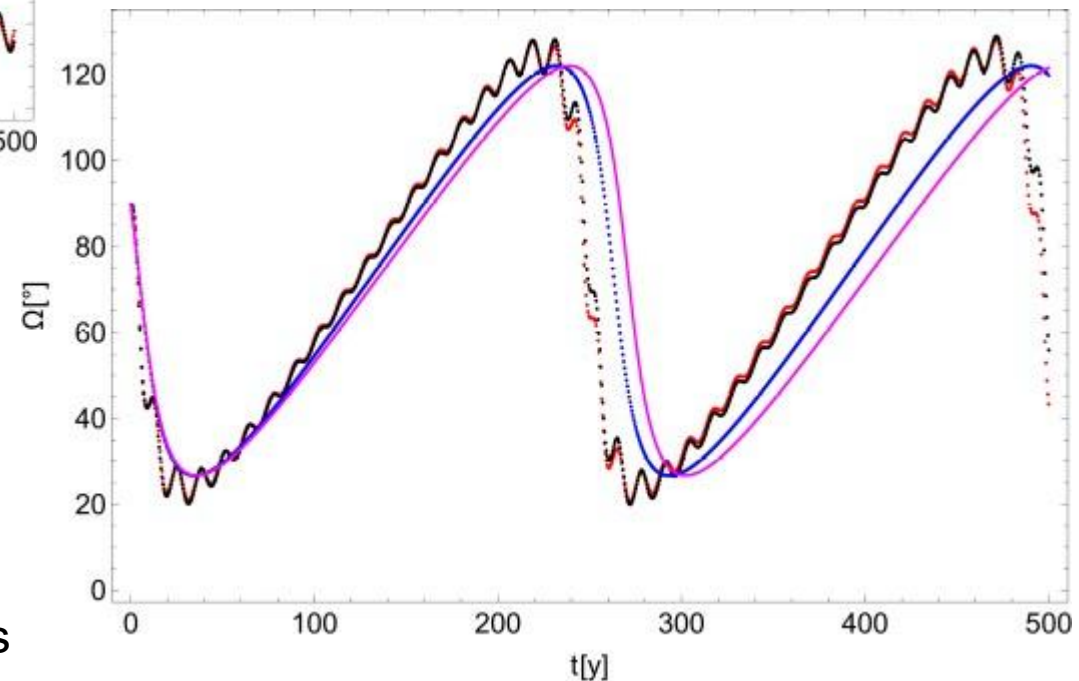
Reduced dynamical model :

$$m\ddot{\mathbf{r}} = \mathbf{F}_{Kep} + \mathbf{F}_L$$

Kepler

Lorentz force

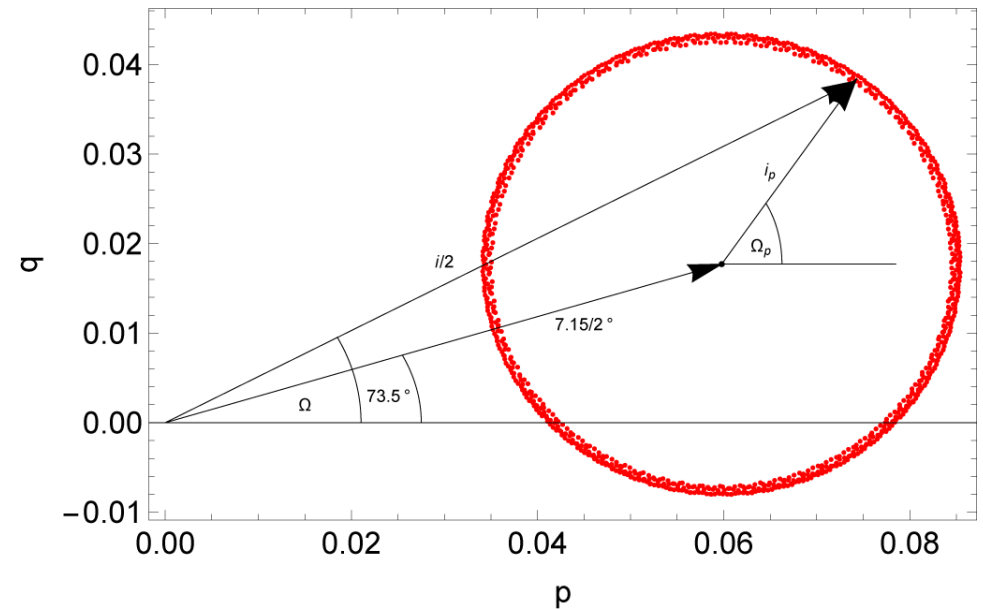
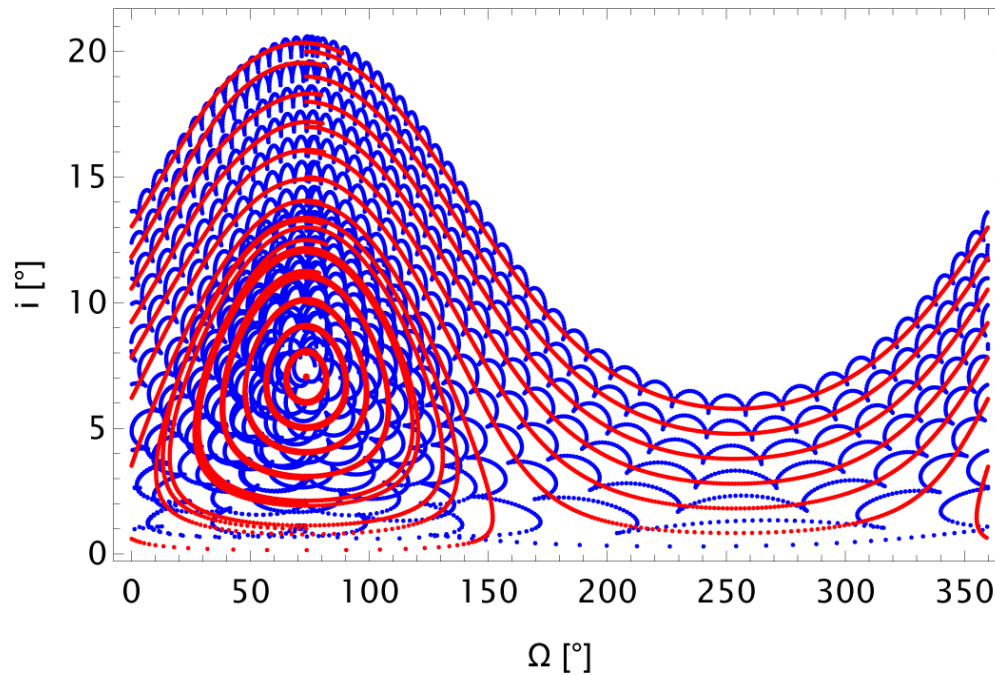
cyclic variations of the orbital plane



Spatial distribution of dust

Reiter, Lhotka 2022

Numerical vs. analytical models



background

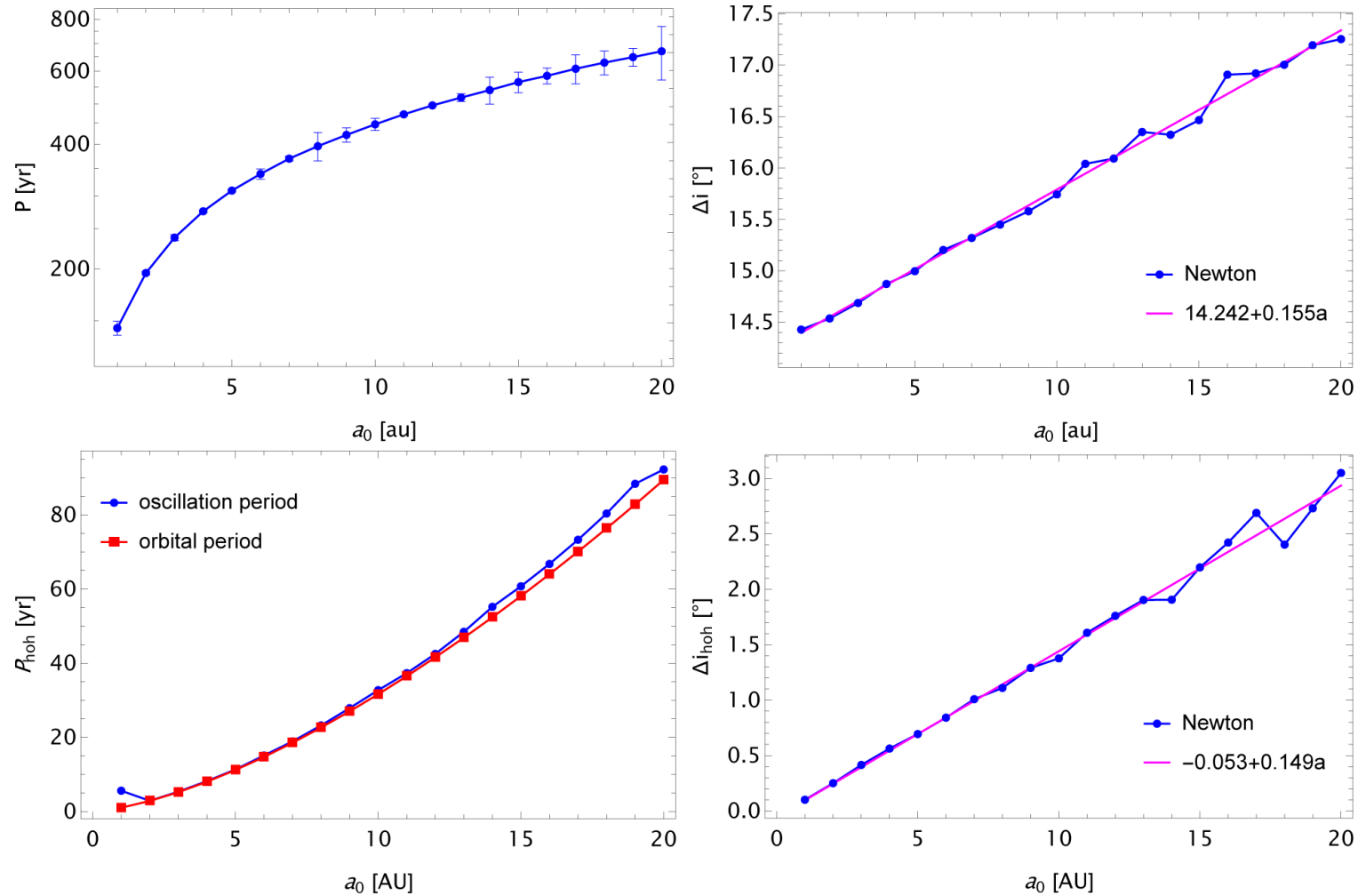
$$\Gamma = \alpha \frac{q}{m} \frac{B_0}{2} \left(\frac{r_0}{a} \right)^2$$

charge-to-mass ratio semi-major axis

Ascending node period and variations in inclinations are given by deviation between angular momentum and magnetic axis

Spatial distribution of charged dust

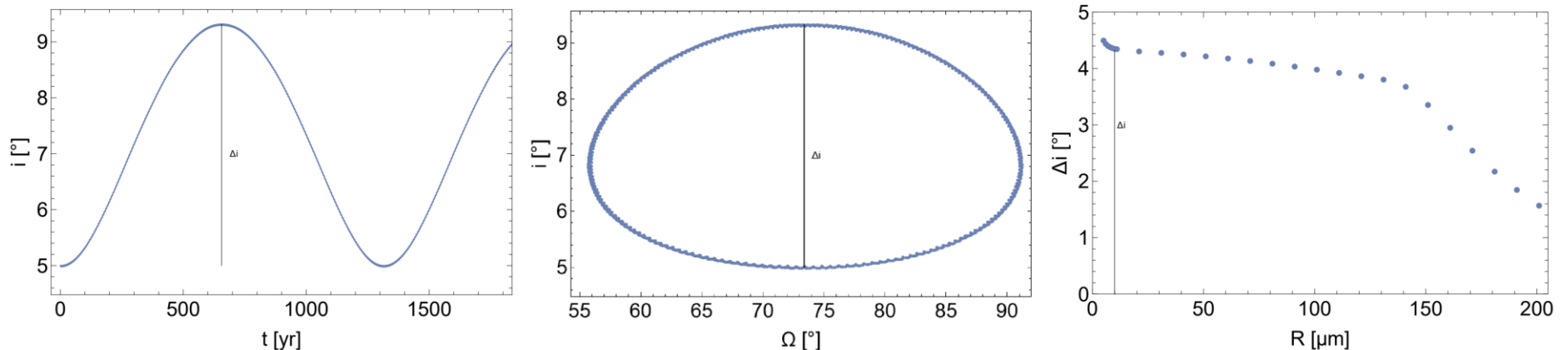
Reiter, Lhotka 2022



Latitudinal excursions depend on solar distance, debris size, and space weather effects

IMF partitions dust in planetary systems

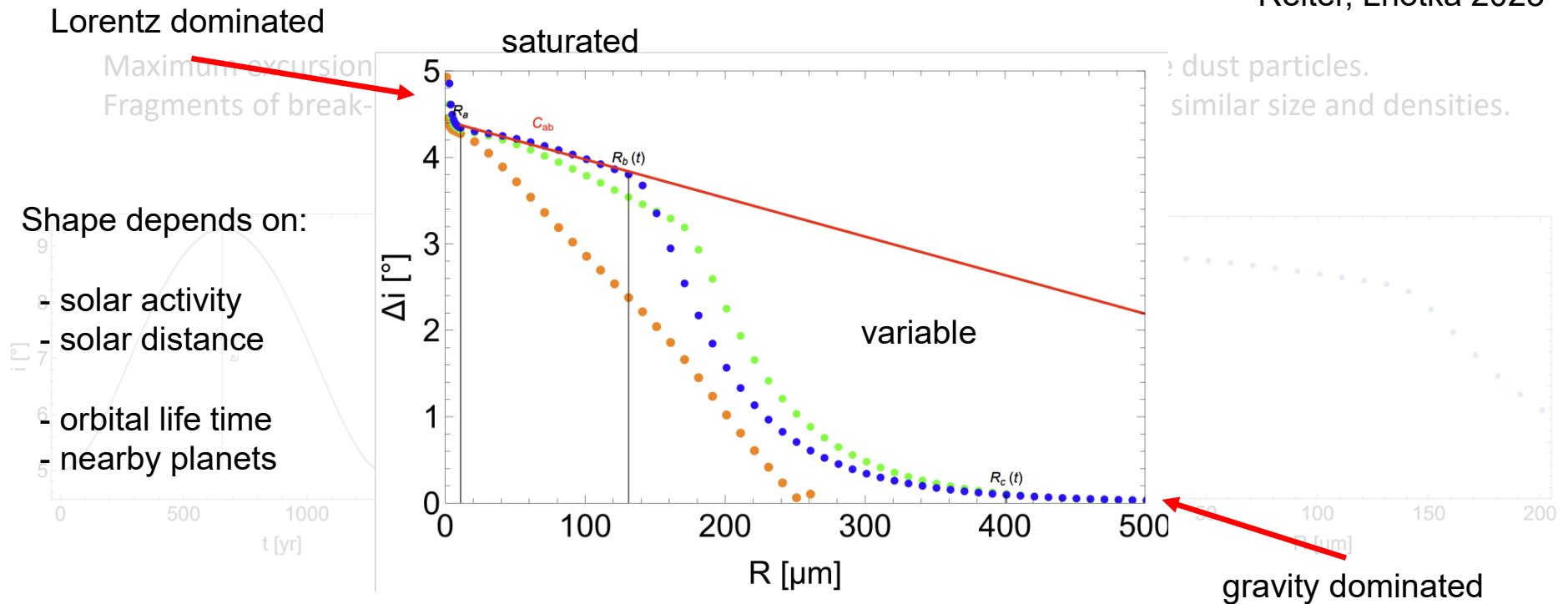
Maximum excursions in latitude (amplitudes) and periods depend on size of the dust particles.
Fragments of break-up events are getting partitioned by the IMF into groups of similar size and densities.



Reiter, Lhotka 2023

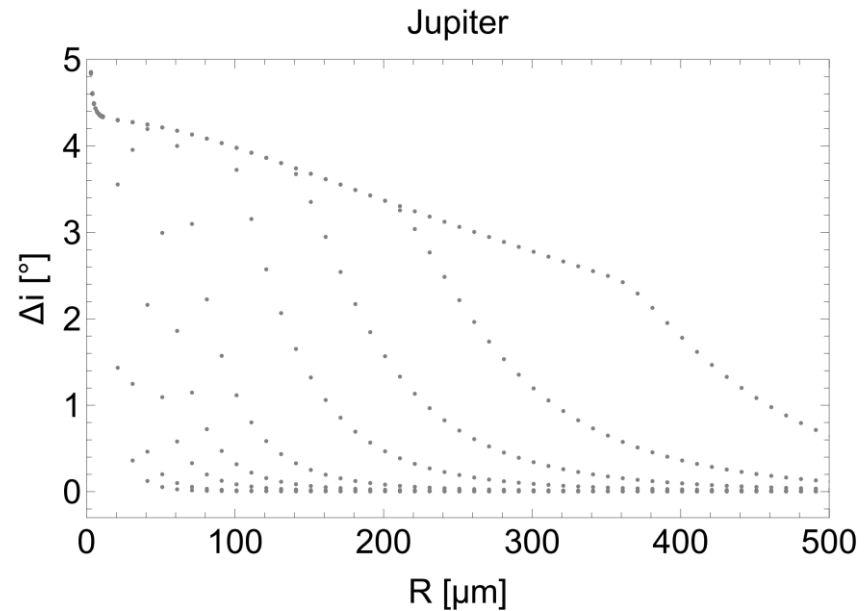
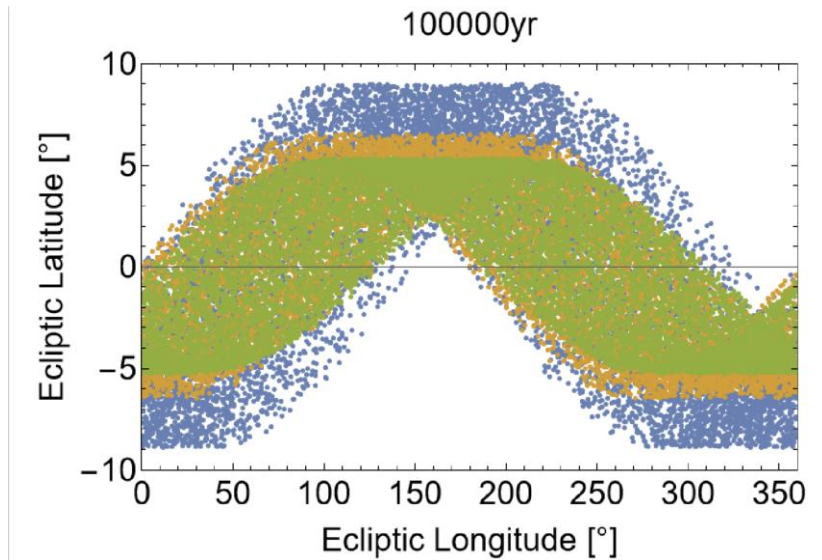
'Saturation curve' of breakup events

Reiter, Lhotka 2023



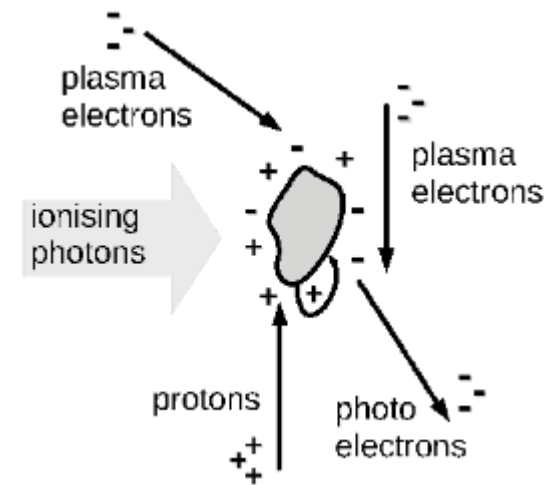
Dust bands formed by the IMF

Dust bands in the zodiacal light formed at different ecliptic latitudes from cometary dust, fragments of break-up events or collisions of asteroids and meteoroids in space.



Reiter, Lhotka 2023

Dust charging model I/II



Set-up of mathematical model for charging processes

Current balance equation:

$$\text{charge} \rightarrow \frac{dq}{dt} = \sum_{k=1}^N I_k \leftarrow \text{currents}$$

Electron current:

$$I_e = -\sqrt{8\pi} r_d^2 q_e n_e v_{Te} \exp\left(\frac{q_e \phi_d}{k_B T_e}\right)$$

plasma parameters

dust parameter

$$I_i = \sqrt{8\pi} r_d^2 q_e n_i v_{Ti} \left(1 - \frac{q_e \phi_d}{k_B T_i}\right)$$

Ion current (protons or ions):

surface potential

Equation for charge number:

$$\frac{dZ_d}{dt} = -\frac{I_e + I_i}{q_e}$$

Lhotka et al. 2020

Dust charging model II/II

Normalized charge number

$$\frac{dz_n}{dt} = -\alpha_n \left(1 + \frac{T_e}{T_i} z_n - \frac{v_{T_e}}{v_{T_i}} e^{-z_n} \right)$$

plasma temperatures

mean particle velocities

$$1 + \frac{T_e}{T_i} z_0 - \frac{v_{T_e}}{v_{T_i}} e^{-z_0} = 0$$

$$z_n = z_0 + z_1$$

$$\frac{dz_1}{dt} = -\alpha_n \left(\frac{T_e}{T_i} + \frac{v_{T_e}}{v_{T_i}} e^{-z_0} \right) z_1$$

$$t_c \propto \frac{1}{\alpha_n \left(\frac{T_e}{T_i} + \frac{v_{T_e}}{v_{T_i}} e^{-z_0} \right)} \quad z_1(t) \propto e^{-t/t_c}$$

Parameter that collects all physics:

$$\alpha_n = \frac{\sqrt{8\pi} r_d n_0 q_e^2 v_{T_i}}{k_B \epsilon_0 T_e}$$

Equation in normalized units

Equilibrium charge condition

Linearized equation of motion

Charging time scale

Lhotka et al. 2020

Charging time scales

Kappa vs. Maxwellian plasma particle distribution functions:

$$t_c = \frac{1}{\alpha_{p,\kappa} [(\kappa - 1) \alpha' + e^{-z_0} \alpha_0]} \quad \text{vs.} \quad t_c \propto \frac{1}{\alpha_p \left(\frac{T_p}{T_e} + e^{-z_0} \right)}$$

with

$$\alpha_{p,\kappa} = \frac{2\sqrt{\pi} q_e^2 r_d n_0 \theta_e}{k_B T_p \varepsilon_0} \quad \alpha' = \frac{T_p}{T_e} \frac{2}{(2\kappa - 3)} \quad \alpha_p = \frac{\sqrt{8\pi} r_d n_e q_e^2 v_{Te}}{k_B \varepsilon_0 T_p}$$

Electron – ion plasma without photoelectric effect:

$$t_c \propto \frac{1}{\alpha_{n,k} \frac{(\kappa-1)}{\kappa} \left[\frac{T_e}{T_i} + \frac{v_{Te}}{v_{Ti}} \left(\frac{z_0 + \kappa}{\kappa} \right)^{-\kappa} \right]} \quad \text{vs.} \quad t_c \propto \frac{1}{\alpha_n \left(\frac{T_e}{T_i} + \frac{v_{Te}}{v_{Ti}} e^{-z_0} \right)}$$

In the limit ($\kappa \rightarrow \infty$) the time-scales (and equilibria) coincide

Lhotka et al. 2020

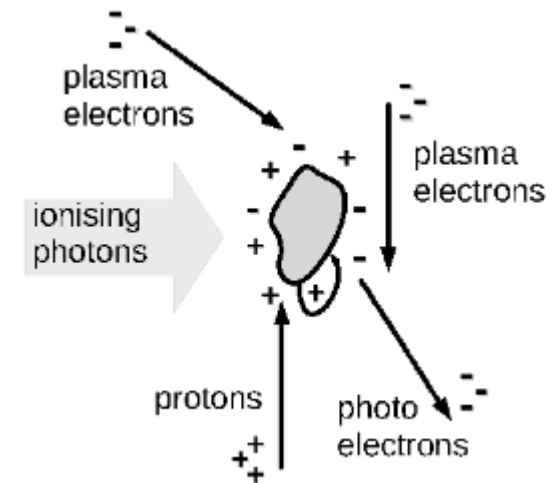
Charging processes I/II

charge currents

Current balance equation : $\frac{dq}{dt} = \sum_k I_k$

Main charging processes in the solar system:

- Impacts of electrons and ions which transfer their charge to the grain
- Photo electron emission induced by solar photons
- Secondary electron currents, etc.



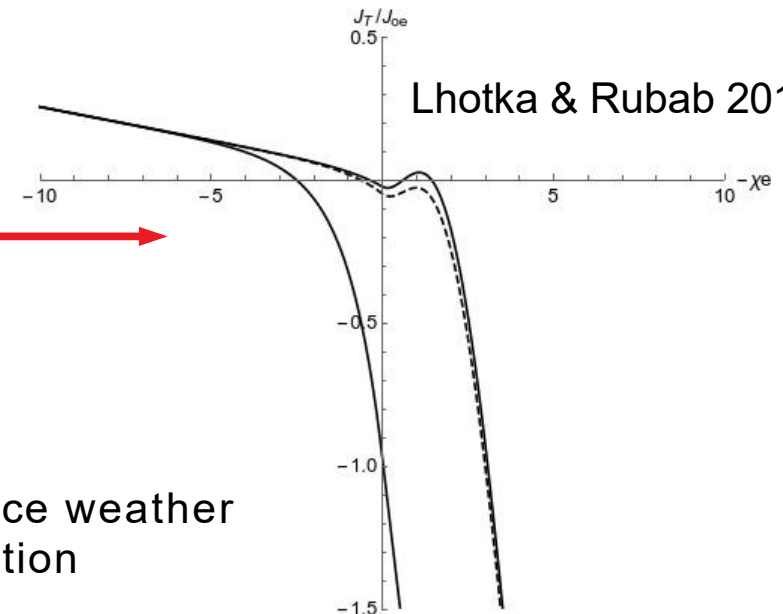
Equilibrium charge when sum of currents vanish:

$$\frac{dq_D}{dt} = I_e + I_i + I_\nu + I_{sec} = 0$$

electrons / ions

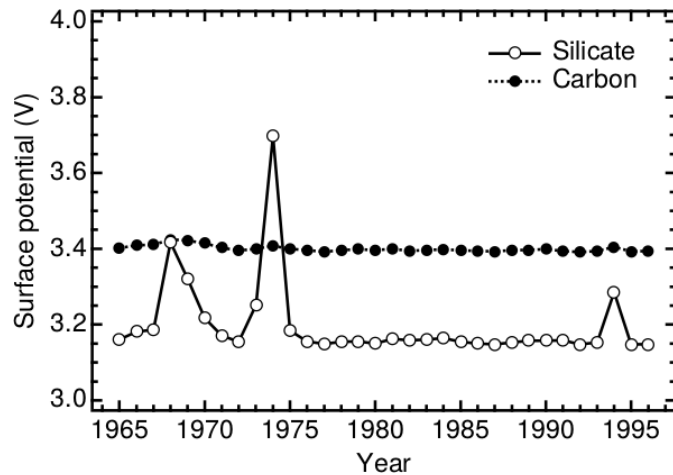
Photo electrons

Secondary emissions



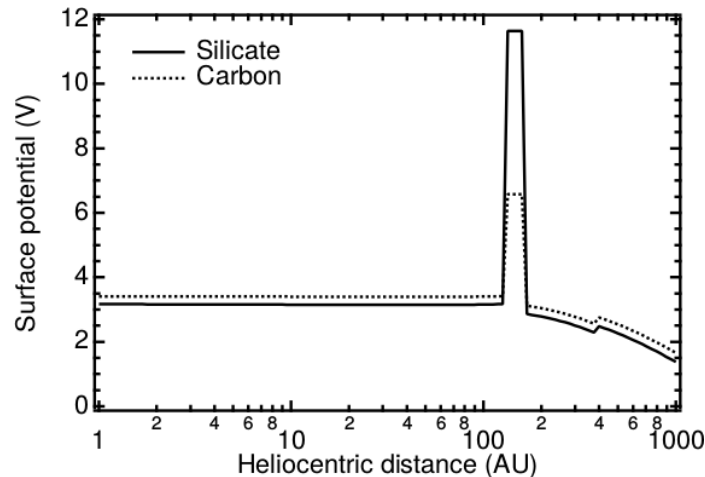
Constant charge depends on distance from the sun, space weather conditions as well as particle size and chemical composition

Charging processes II/II

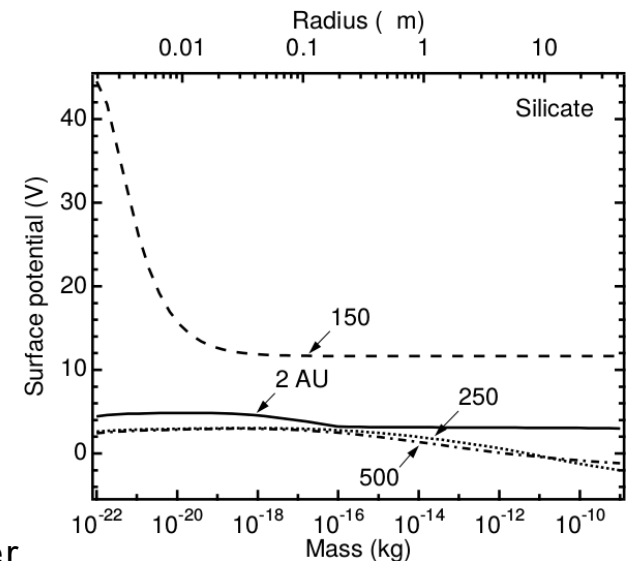
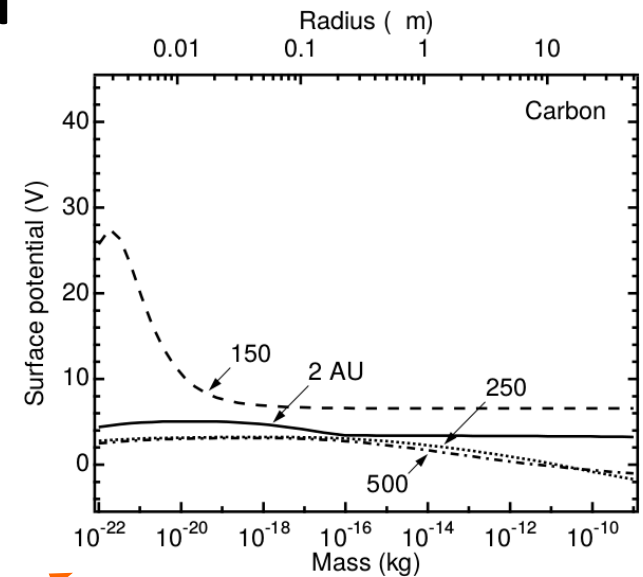


Temporal variation due to different solar wind conditions of the surface potential of a grain having mass of 3×10^{-16} kg located at 1 AU.

Surface potential of interstellar dust grains vs. grain size at different heliocentric distances from the sun.



Surface potential of interstellar dust grains having mass 3×10^{-16} kg vs. heliocentric distances ranging from 1 to 1000 AU.



Constant charge depends on distance from the sun, space weather conditions as well as particle size and chemical composition

Maxwellian distribution

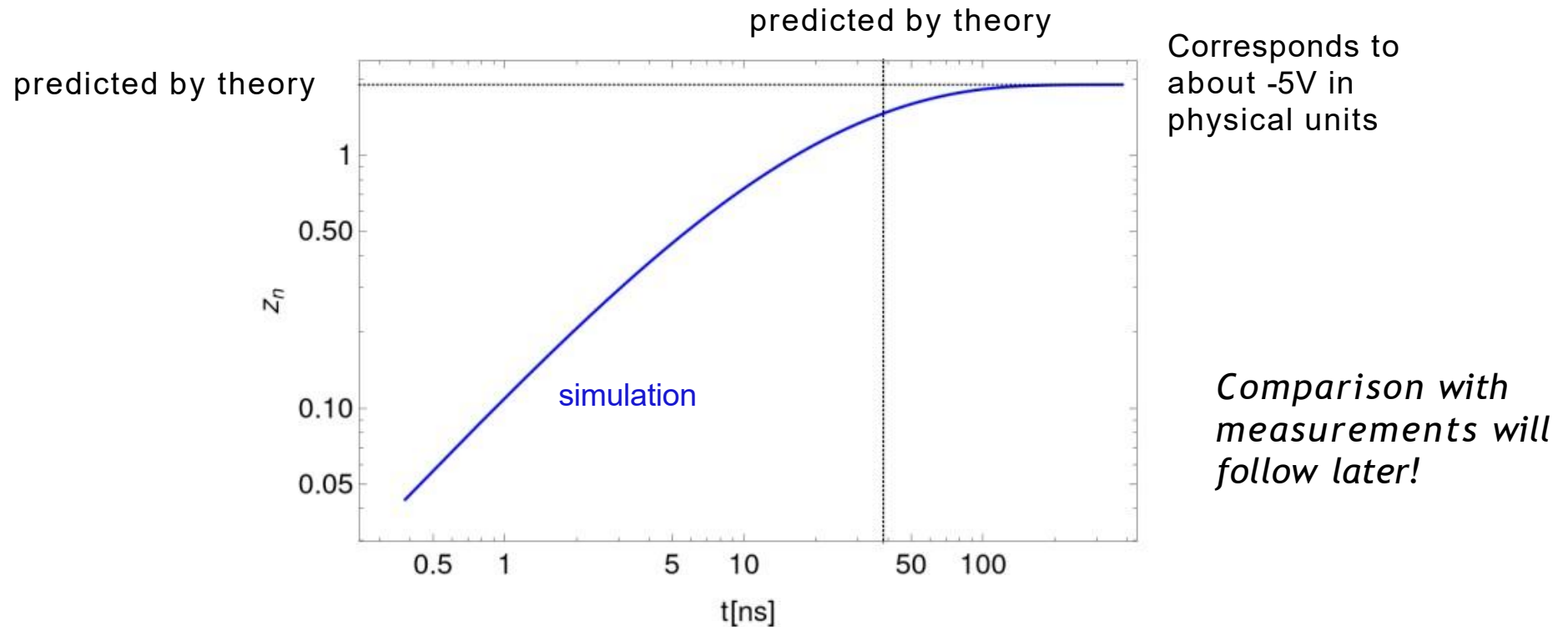
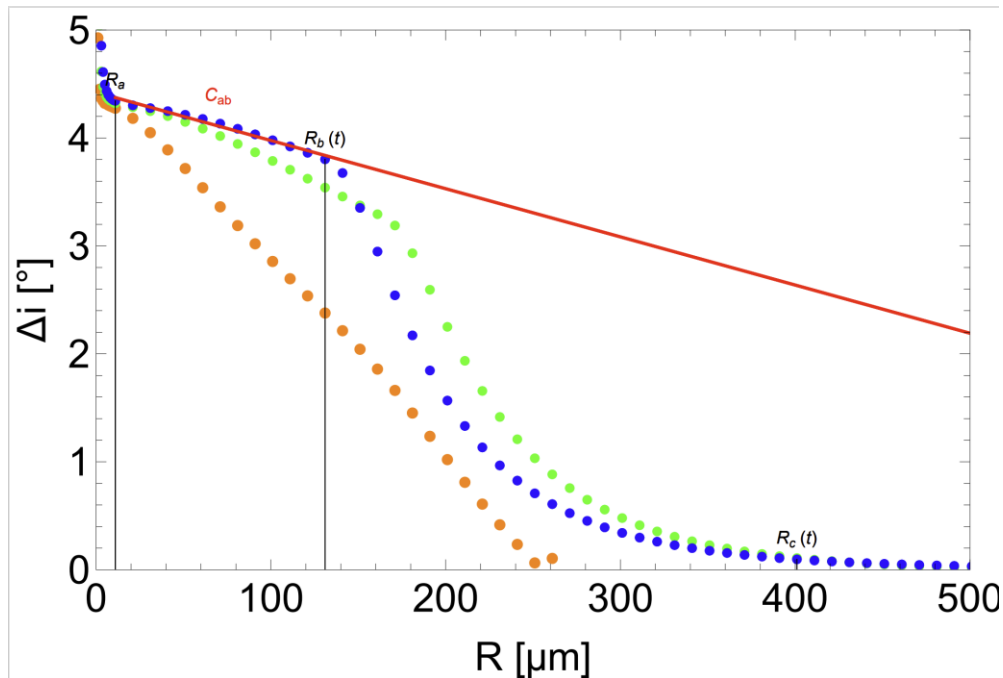


Fig. 1: Charging history for the case 1a-r with $r_d = 1\mu\text{m}$, $T_e/T_i = 10$, $n_0 = 5 \cdot 10^9 \text{cm}^{-3}$, and $m_i = m_p$ (the proton mass).

Further reading

Reiter & Lhotka 2023 <https://doi.org/10.1093/mnras/stad1848>



Beauge & Ferraz-Mello 1994
<https://doi.org/10.1006/icar.1994.1119>

Klacka et al. 2014
<https://doi.org/10.1016/j.icarus.2012.06.044>

Lhotka & Celletti 2015
<https://doi.org/10.1016/j.icarus.2014.11.039>

Lhotka et al. 2016
<https://doi.org/10.3847/0004-637X/828/1/10>

Lhotka & Narita 2019
<https://doi.org/10.5194/angeo-37-299-2019>

Lhotka & Gales 2019
<https://doi.org/10.1007/s10569-019-9928-y>

Lhotka & Rubab 2019
<https://doi.org/10.1063/5.0018170>

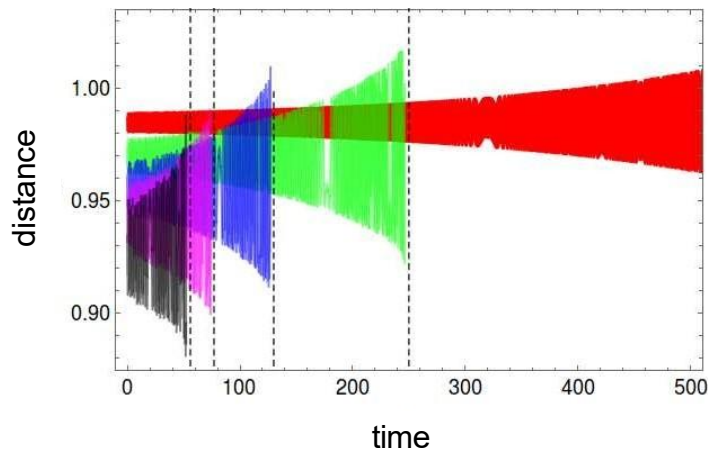
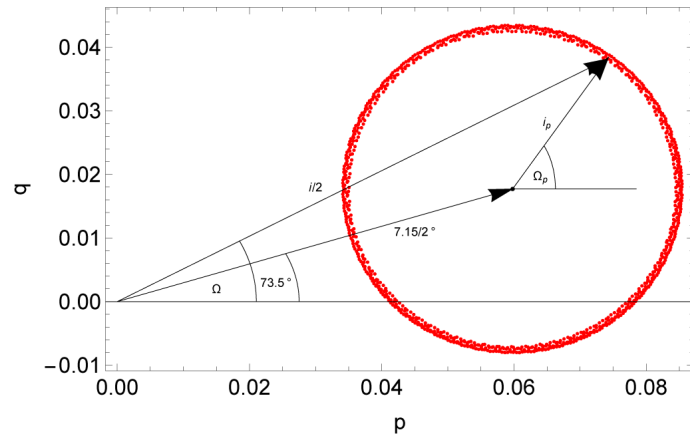
Lhotka & Zhou 2021
<https://doi.org/10.1016/j.cnsns.2021.106024>

Pokorny & Kuchner 2019
<https://doi.org/10.3847/2041-8213/ab0827>

Reiter & Lhotka 2022
<https://doi.org/10.1051/0004-6361/202243693>

Zhou & Lhotka 2021
<https://doi.org/10.1051/0004-6361/202039617>

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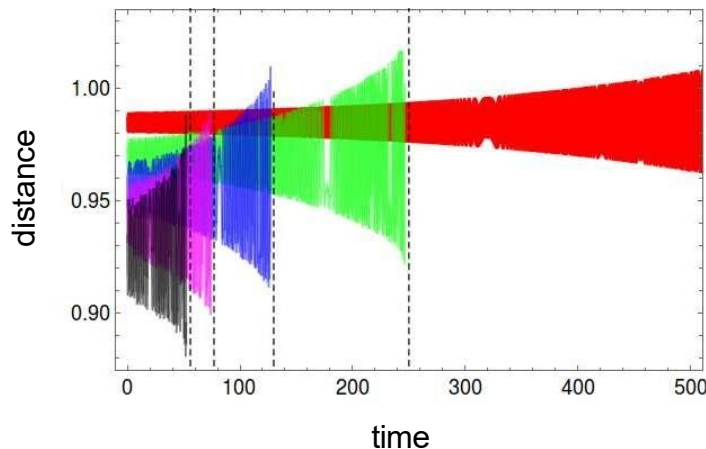
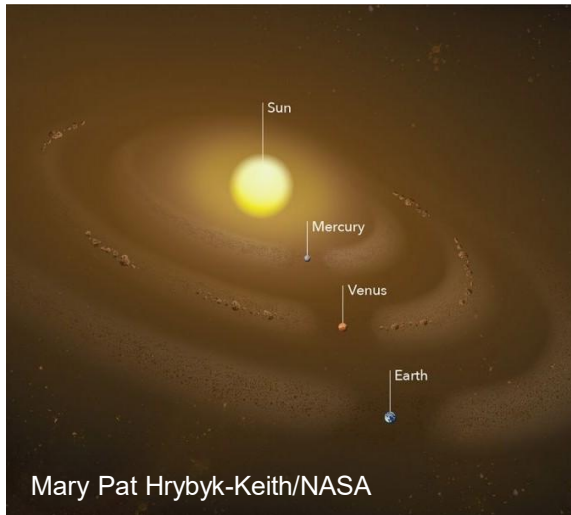
Reiter & Lhotka 2022

<https://doi.org/10.1051/0004-6361/202243693>

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Further reading



Beauge & Ferraz-Mello 1994

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Fedele et al. 2017

<https://doi.org/10.1051/0004-6361/201629860>

Klacka et al. 2014

<https://doi.org/10.1016/j.icarus.2012.06.044>

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Accepted (arxiv: <https://doi.org/10.1016/j.cnsns.2021.106024>)

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Zhou & Lhotka 2021

<https://doi.org/10.1051/0004-6361/202039617>

In plane vre

Classical (time dependent) Parker spiral model :

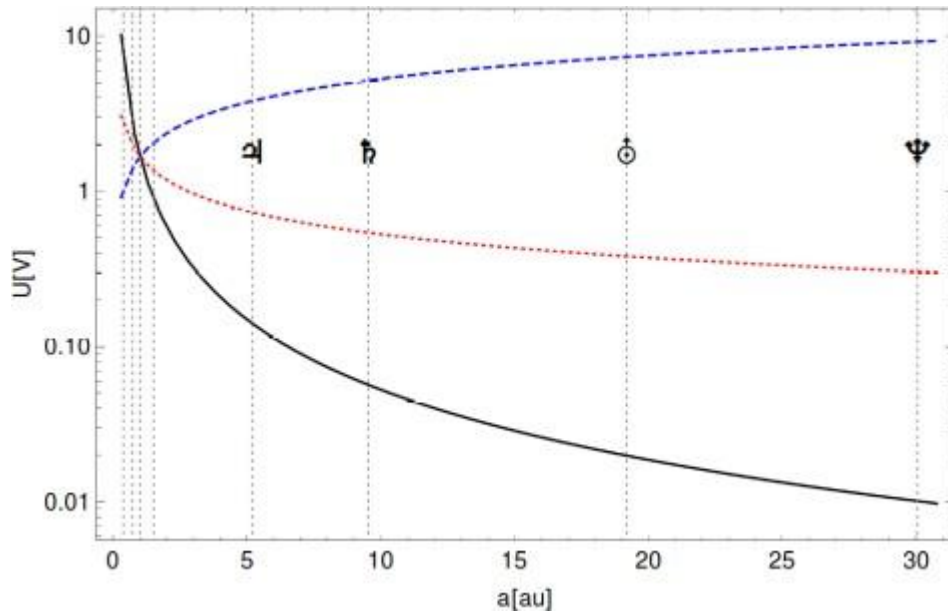
$$B_R = B_0 \left(\frac{r_0}{r} \right)^2 b_R(t) \quad b_R(t) = \cos(2\pi t/T + \varphi_0)$$

$$B_T = B_0 \left(\frac{r_0}{r} \right) b_T(t) \quad b_T(t) = \cos(\vartheta) \cos(2\pi t/T + \varphi_0)$$

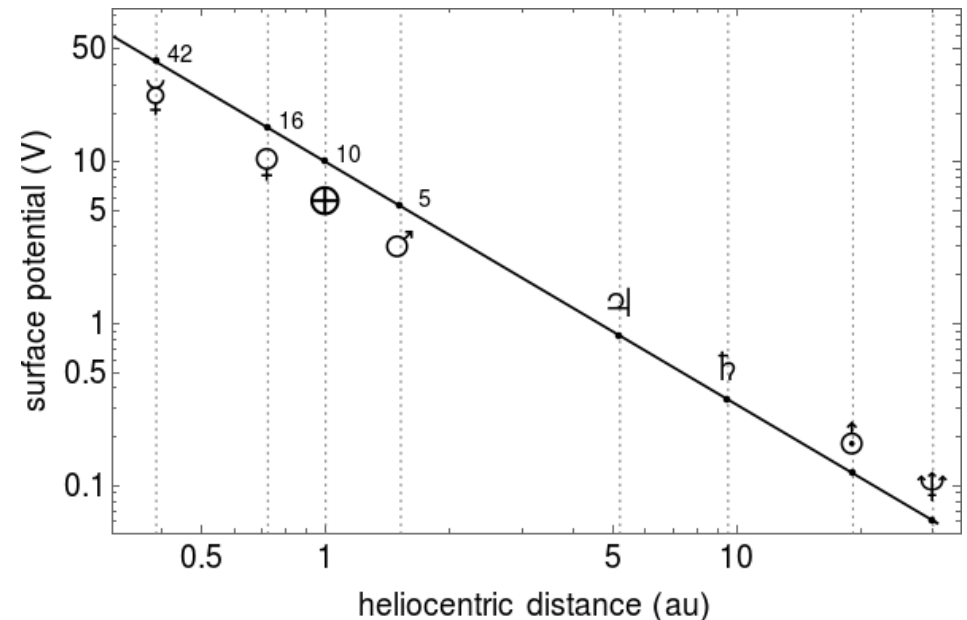
Importance of the normal component :

$$B_N = B_0 \left(\frac{r_0}{r} \right)^\kappa b_N(t) \quad b_N(t) = 1 + \cos(2\pi t/T)$$

Study in distance for different κ (1=black, 2=red, 3=blue) :

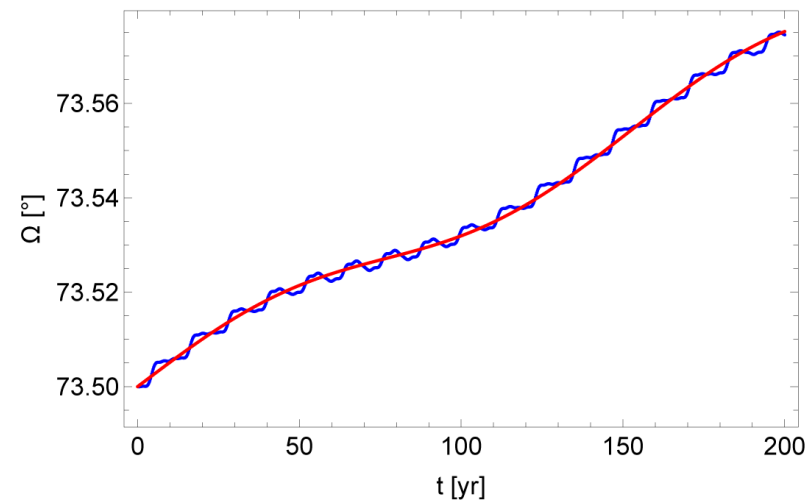
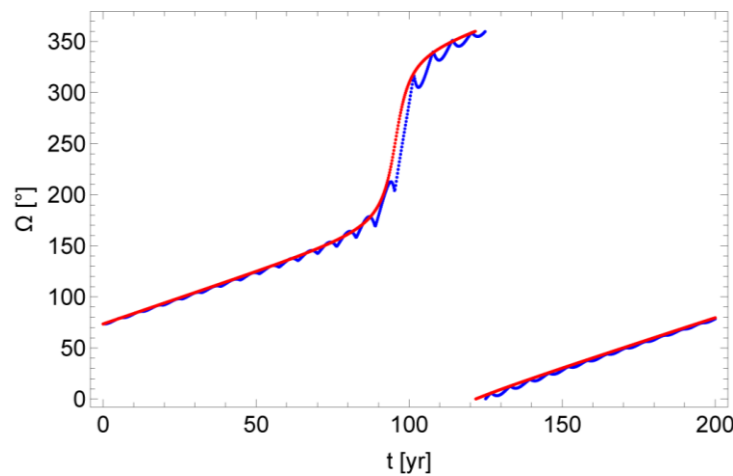
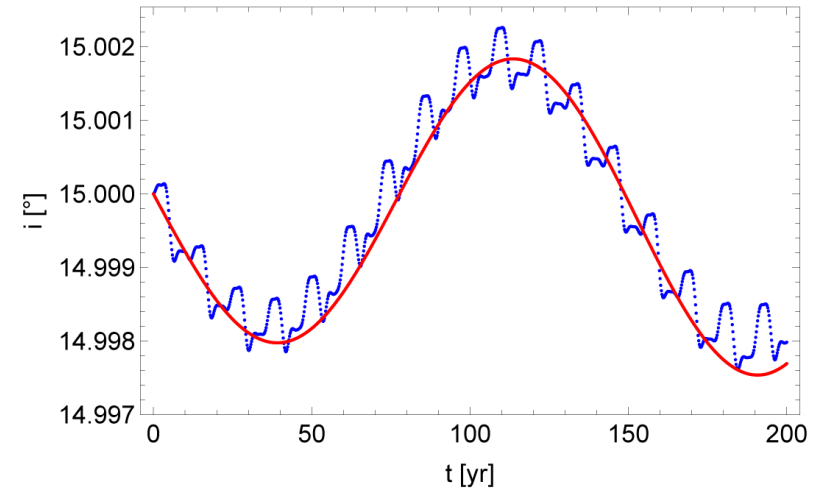
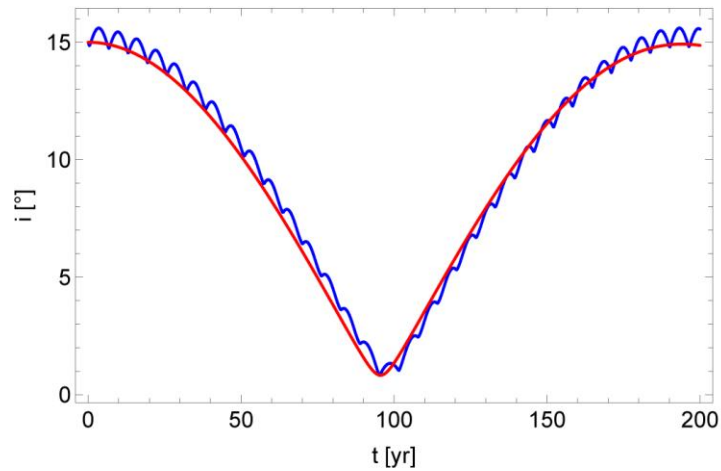


- Mimics solar cycle with period T
- Radial component falls with $1/r^2$
- Tangential component falls with $1/r$
- Normal component falls with $1/r^\kappa$
- Non-zero mean of normal component



Out-of-plane motion

Reiter, Lhotka 2022



Lorentz force due to interplanetary magnetic field brings dust to high ecliptic latitudes