UN PROBLEME SEVERE:
2 Ordinateurs → 2 orbites differentes

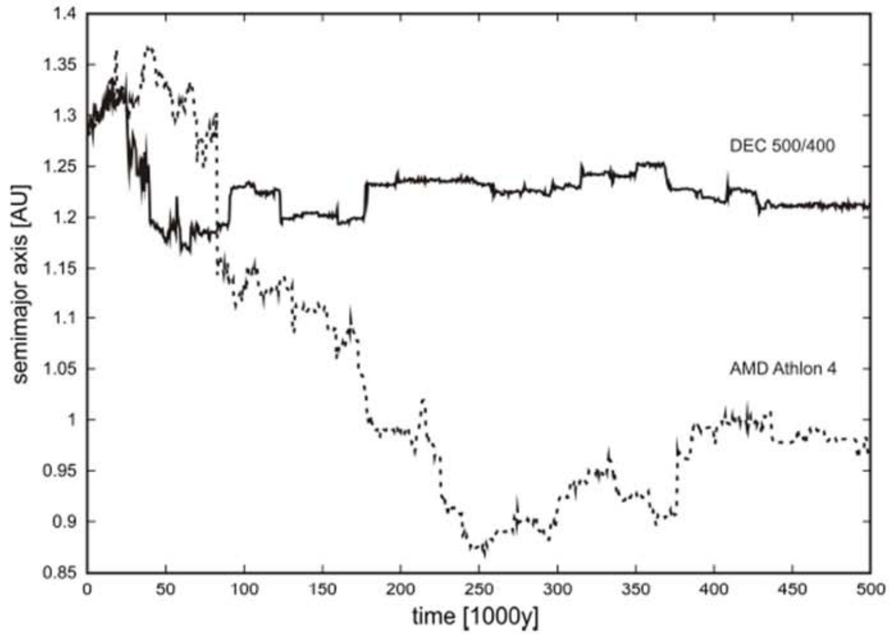
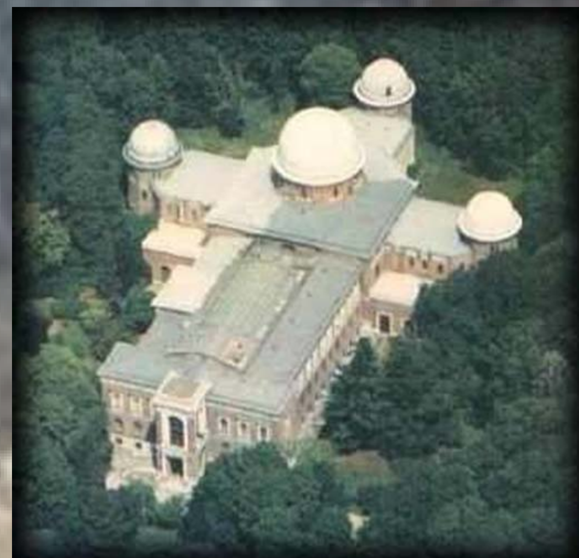


Fig. 1 Evolution of the semimajor axis of a NEA. The two curves were obtained with the same method and initial conditions but on different computers.

Meme dans un modele simple – loi de Newton –masses ponctuelles - asteroide sans masse

AsteRisk
Atelier CIA MEUDON Juin 2011



Rudolf Dvorak, Akos Bazso ,Mattia Galliazzo, Siggi Eggl
AstroDynamicsGroup
Institute for Astronomy, University of Vienna

ORBITES ET PROBABILITES D'IMPACTS

- Prologue (Un probleme principale)
- Comparison des integrateurs
- Les Hungarias et les impacts
- Le role de la Lune
- Resume

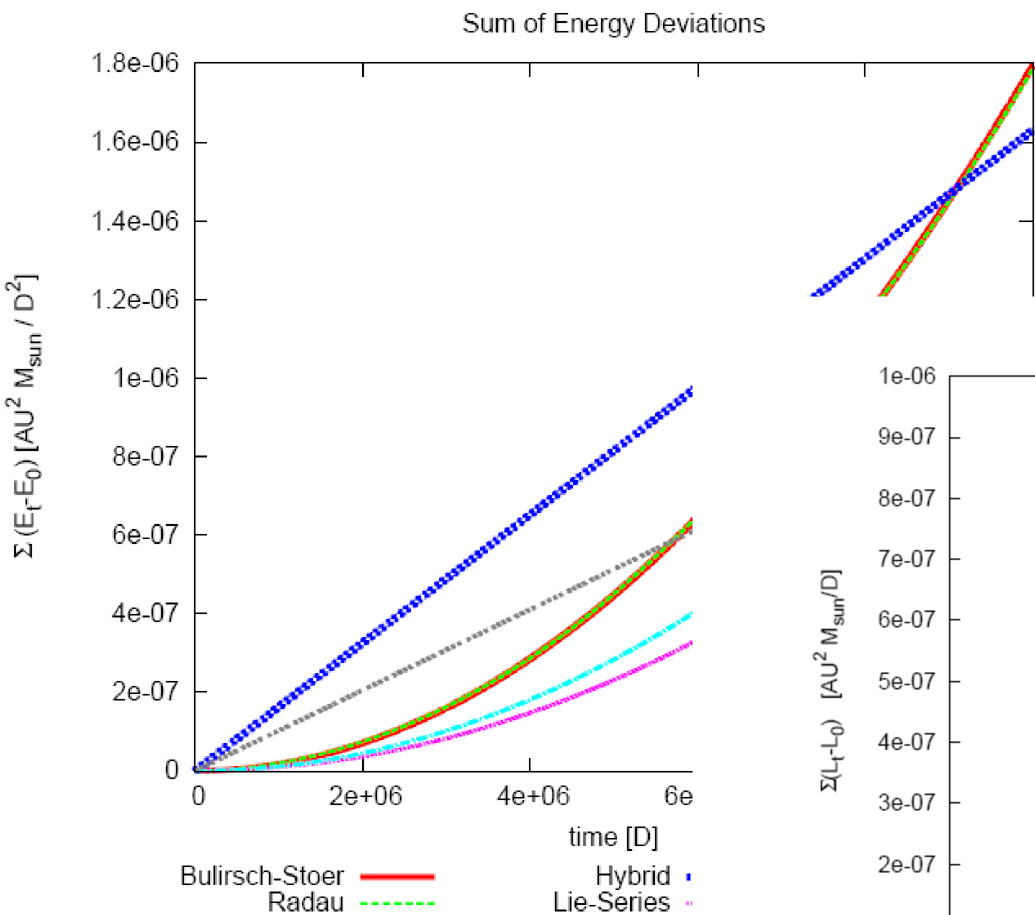
Eggl, Dvorak: 2010*: An Introduction to Common Numerical Integration Codes Used in Dynamical Astronomy*, in Dynamics of Small Solar System Bodies and Exoplanets by J. Souchay and R. Dvorak (Eds.), Lecture Notes in Physics Vol. 790 pp.431-480

Comparison of 6 different Numerical Integration methods:

Bulirsch-Stoer
Radau
Hybrid
Lie-Series
Runge-Kutta
Candy

Mercury 6

Nie-Integrator



Test :
Keplerproblem ->

Energie
Moment cinetique

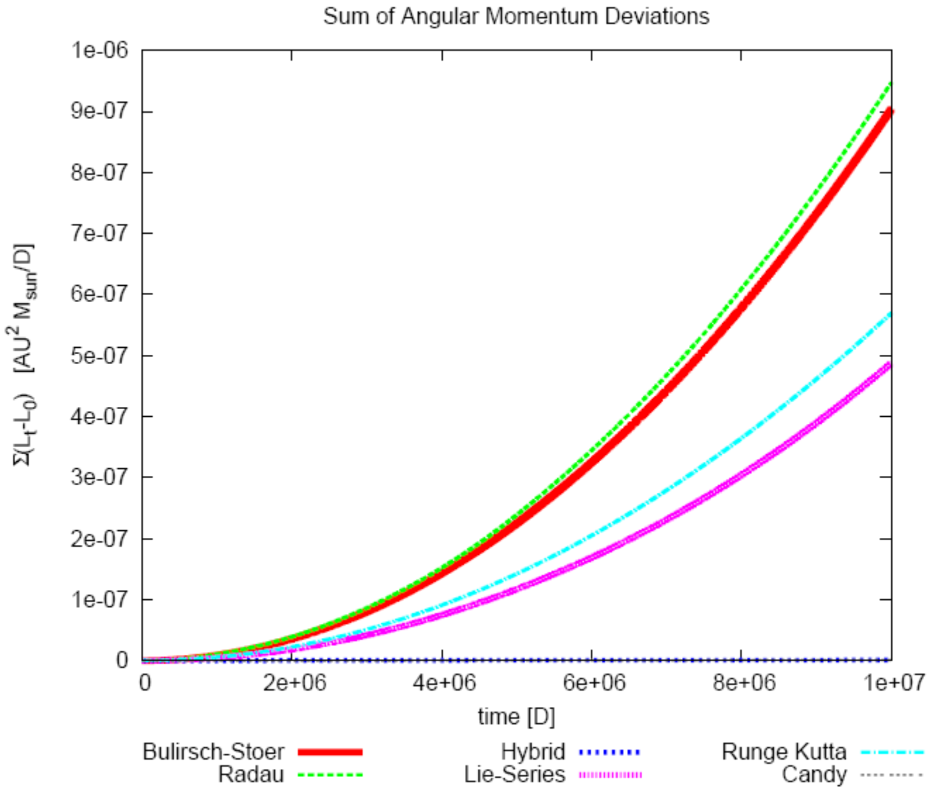
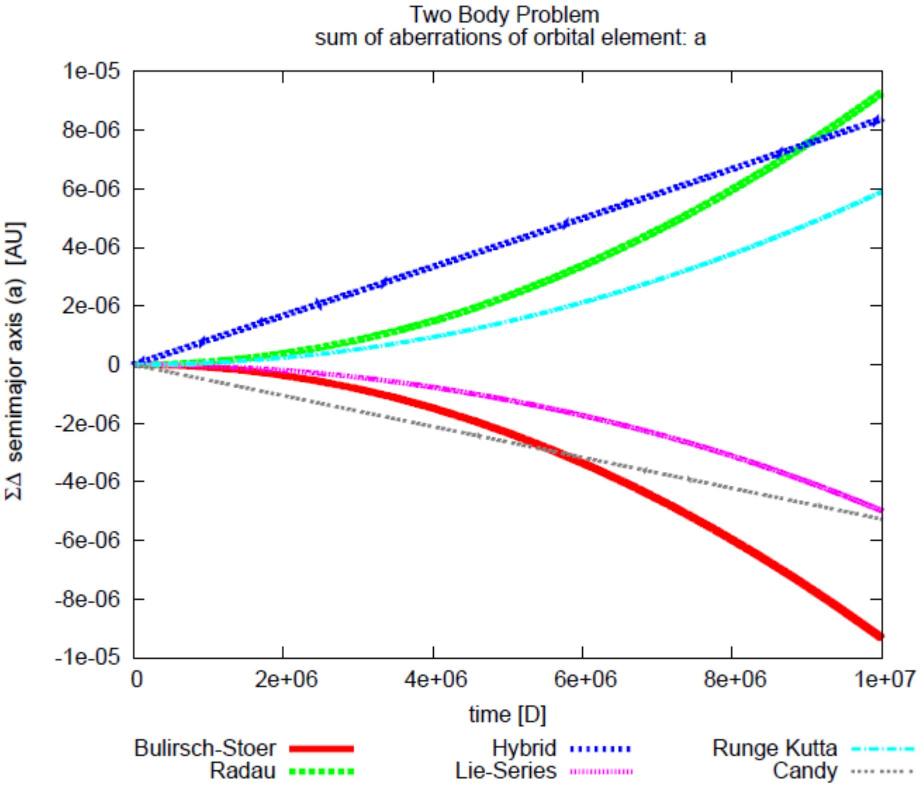


Fig. 3: Sum of deviations of total energy from its initial value for all integration algorithms (above); sum of deviations of total angular momentum from its initial value for all integrators (below); the accuracy parameters of all algorithms were chosen, such that the total sum of deviations of energy at time 10^7 [D] are roughly in the same order of magnitude. The symplectic algorithms show a linear trend in the deviation of total energy, whereas the non-symplectic show a quadratic trend.

- Test :
- Keplerproblem ->
-
- Energie
- Moment cinetique

- Demie grande axe
- Eccentricite
- Inclinaison
- Noeud
- Perihelie



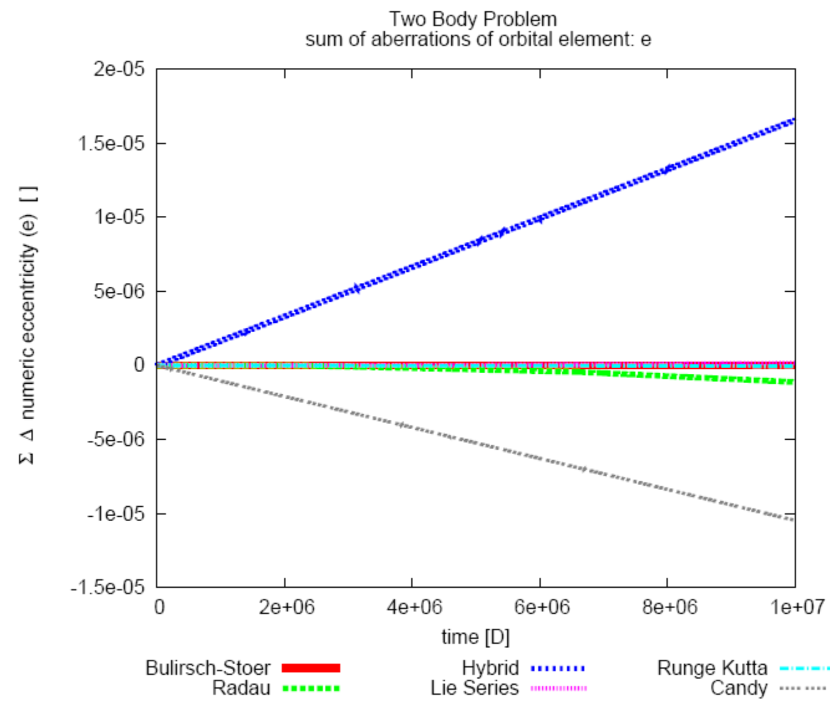
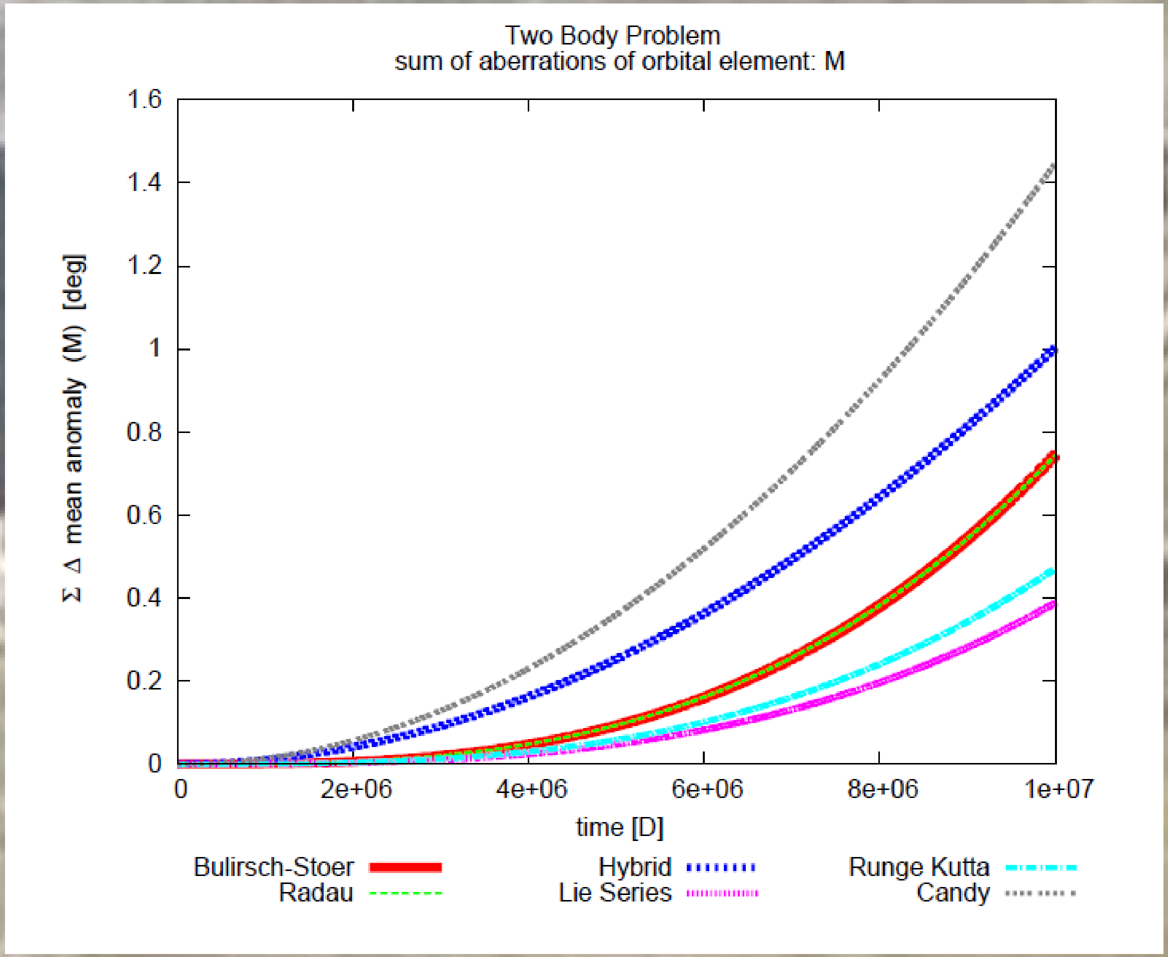
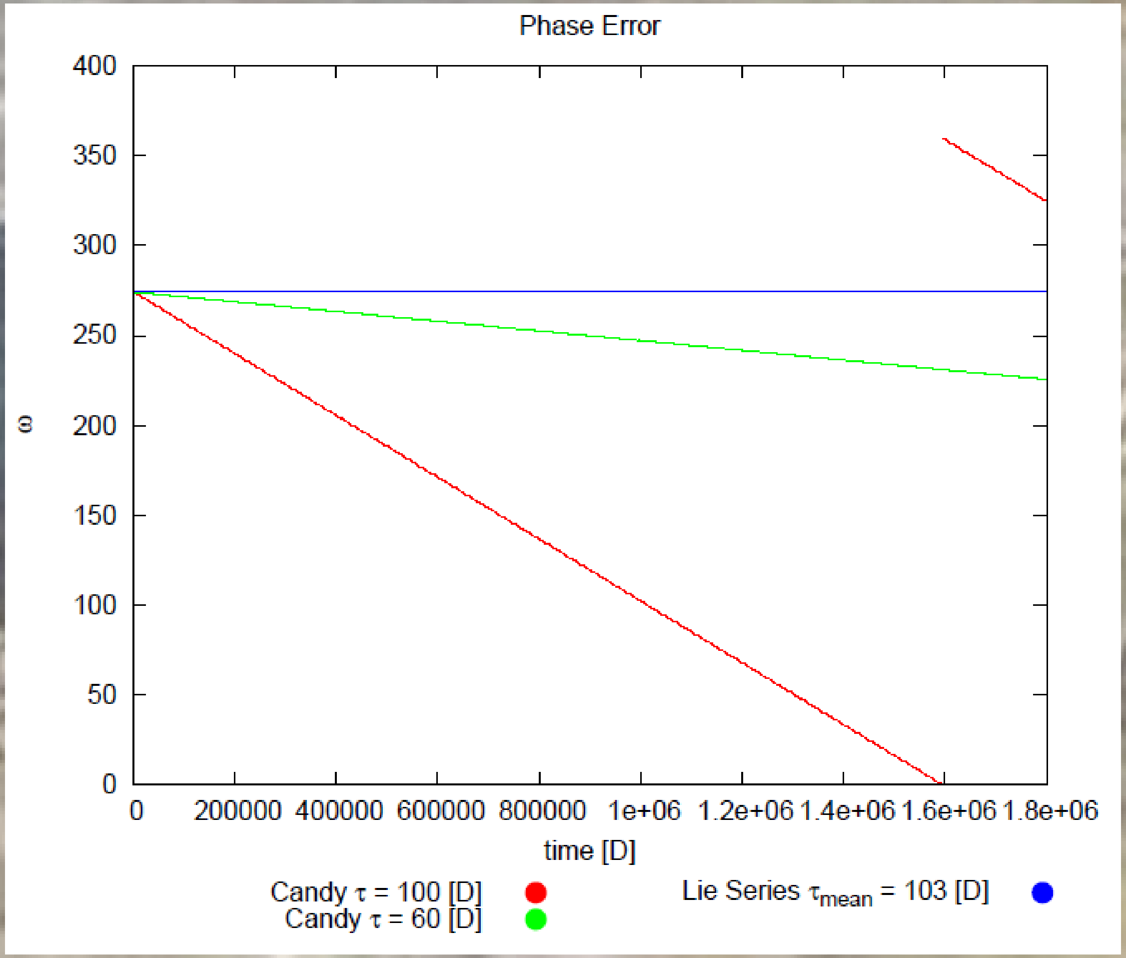


Fig. 6: Sum of deviations of orbital elements a and e from their initial values for all integration algorithms.


Two Body Problem
sum of aberrations of orbital element: M
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Σ Δ mean anomaly (M) [deg]
0
2e+06
4e+06
6e+06
8e+06
1e+07
time [D]
Bulirsch-Stoer
Radau
Hybrid
Lie Series
Runge Kutta
Candy



Phase Error
400
350
300
250
200
150
100
50
0
ω
0
200000
400000
600000
800000
1e+06
1.2e+06
1.4e+06
1.6e+06
1.8e+06
time [D]
Candy τ = 100 [D]
Candy τ = 60 [D]
Lie Series τmean = 103 [D]

Integrator	symplectic	variable step-size	pros	cons
Cash-Karp Runge-Kutta	no	yes	easy implementation adaptability	performance
Gauss Radau	no	yes	accuracy above order, stability	adaptability
Bulirsch-Stoer	no	yes	fast	weak performance when many substeps are required
Lie-Series	no	yes	high performance	specifically designed for a given problem
Candy	yes	no	energy and angular momentum conservation	fixed step-size, symplectic phase-error
Hybrid	yes	yes	energy and angular momentum conservation	specifically designed for a given problem, symplectic phase-error

Table 3: A rough summary of the main properties of the 6 common N-body integration algorithms described in this paper.

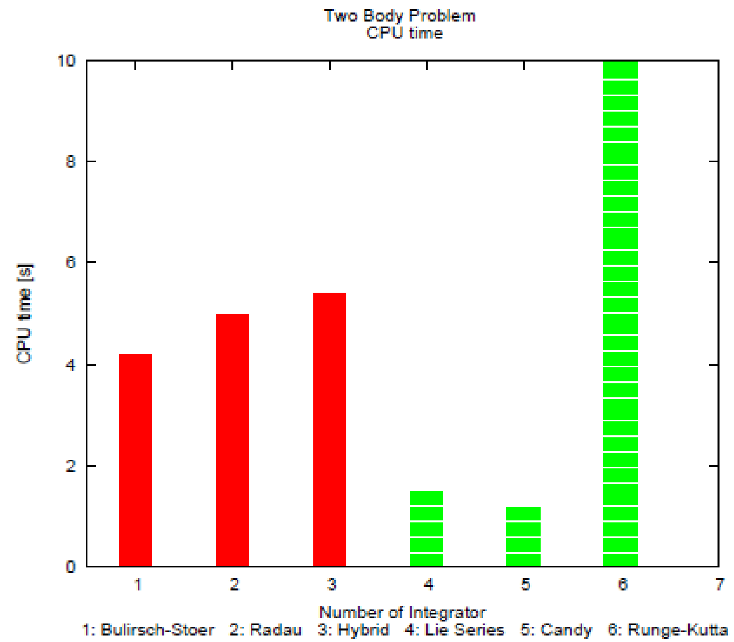


Fig. 11: CPU-time needed to calculate the Sun-Jupiter system up to 10^7 [D].
red histogram: CPU-time consumption of algorithms contained in the *mercury6* package
green histogram: CPU-time consumption of algorithms contained in the *nie* package

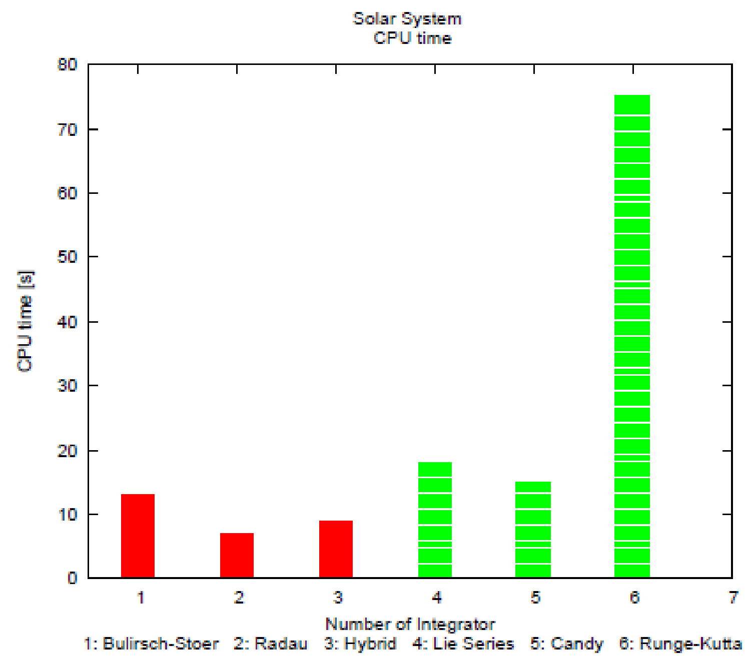


Fig. 12: CPU-time needed to calculate the Solar System up to 10^6 [D].
red histogram: CPU-time consumption of algorithms contained in the *mercury6* package
green histogram: CPU-time consumption of algorithms contained in the *nie* package

La famille des Hungarias et les impacts

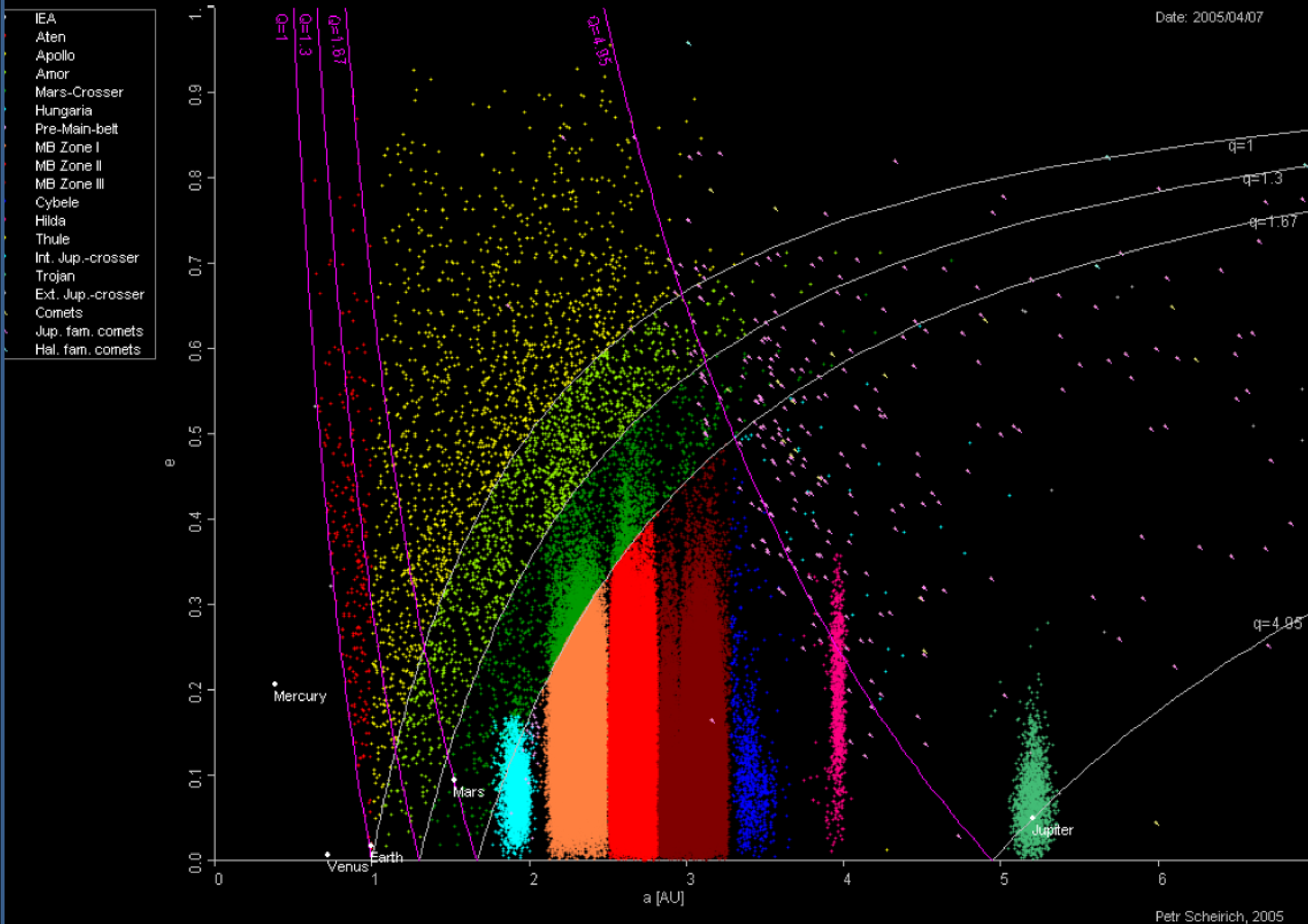
Le role de la Lune

Doctoral School
"*Planetology: From Asteroids to Impact Craters (NEO asteroids and Impact Crater Studies)*"
at the University of Vienna

- **Goals**
  - collaboration with Department of Earth Sciences
  - NEAs and their threat to Earth
  - connection of NEAs and parameters for impact crater studies
  - possible effects of the Moon at present & in the past

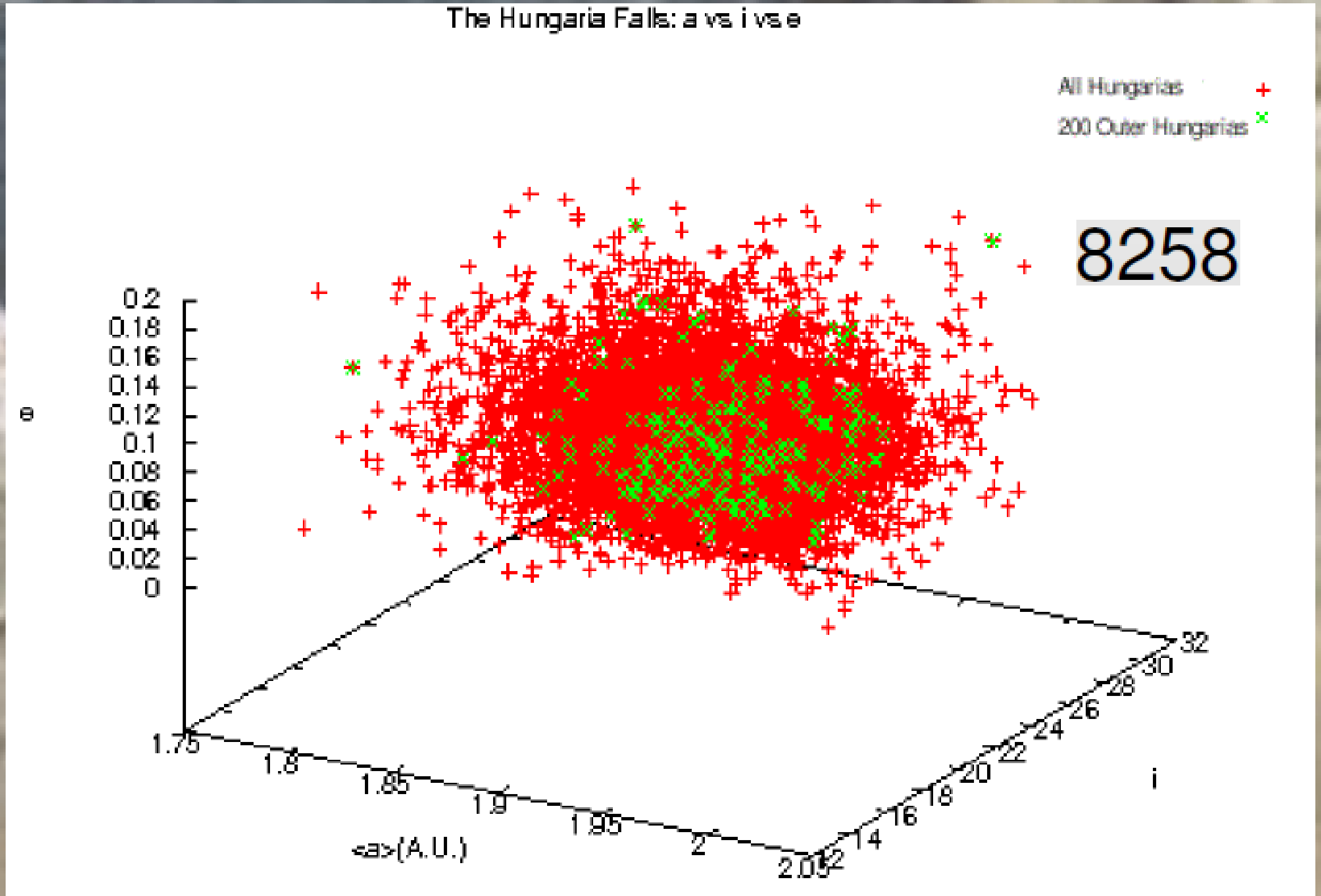
M. Galliazzo et A. Bazso

MBAs –> Dangerous Families-> Hungarias



Hungaria

- a=1.78-2.03A.U.
- i=16°-31°
- e=0-0.19



Integration – Lie prog.

10^8y -Outp.:5*10^3y

4 Groups of 50 massless bodies with the highest metric+Sun,Mars,Jupiter and Saturn

11 large deviations

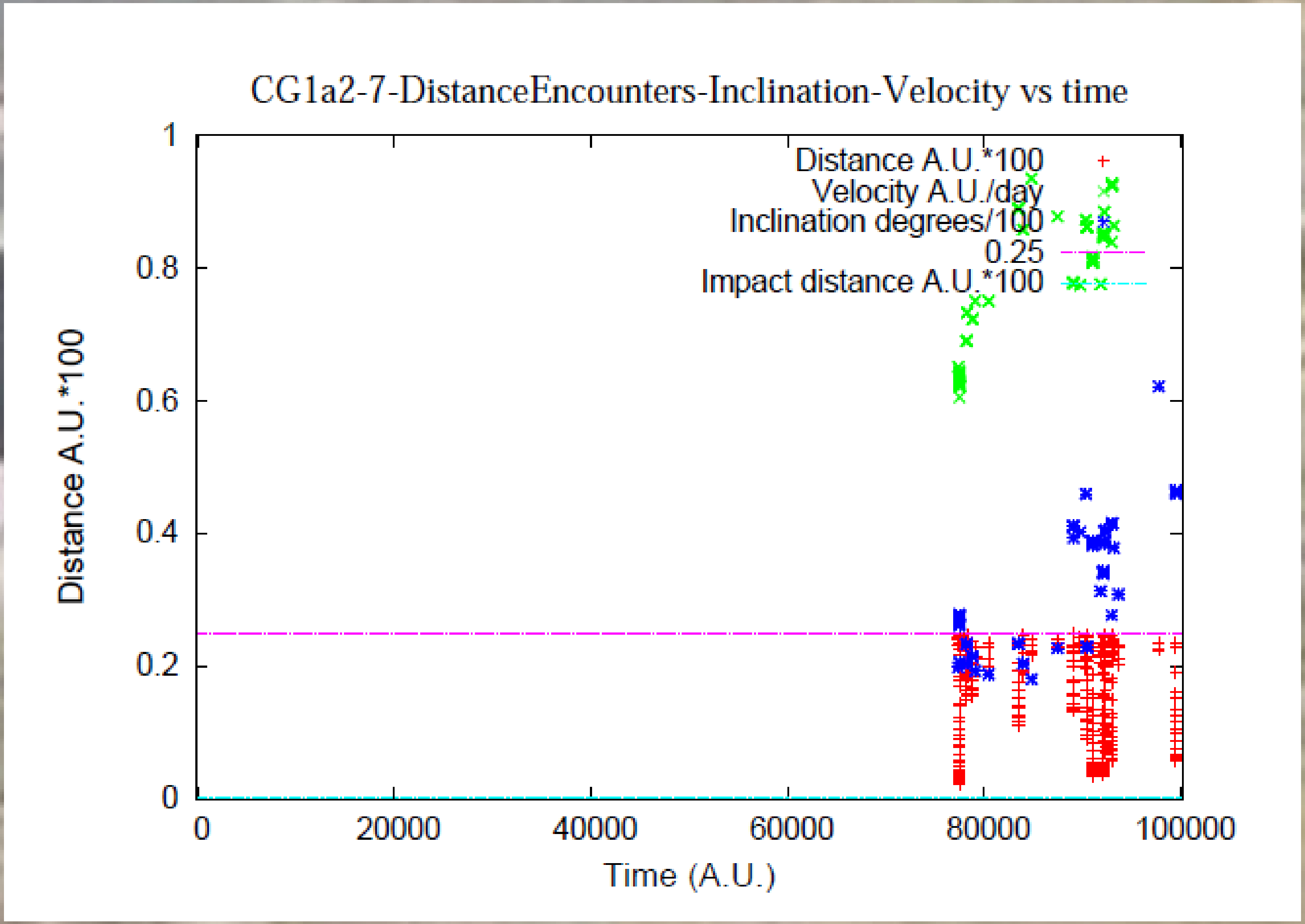
- Clones-deviations:
  - $a_{H,i} \pm 0.005$
  - $e_{H,i} \pm 0.003$
  - $i_{H,i} \pm 0.005$
- Clones-Integration - SuperLie (Zooming steps for close-encounters: <0.0025A.U.)
- 10^8y -Outp.:10^3y
- 5 Groups of 10 massless bodies +Sun,Venus,Earth,Mars,Jupiter Saturn.
- First group: "Real asteroid" + 9clones. Other groups: 10 clones each one.
- 49 clones for all 11 asteroids (largest deviation in <a>) in the First principal integration.

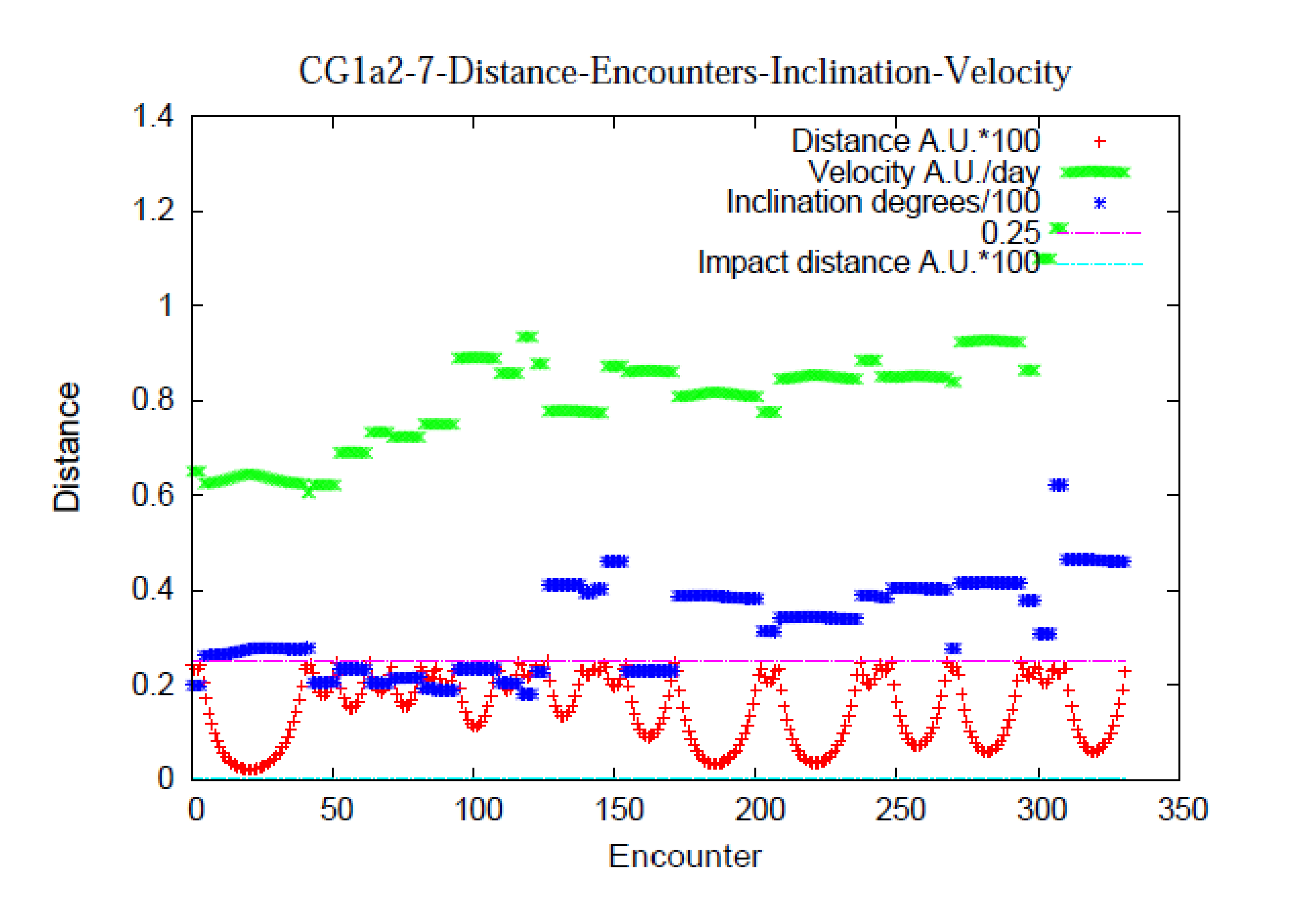
Planet	Asteroid	<Enc>	Max Enc	Min Enc	<Dur>	Max Dur	Min Du
Earth	2002 RN137	0	-	-	-	-	-
	$Clones_{av}$	70	207	2	0.3812266	0.8193286	0.152660
	2000 WN 124 0	-	-	-	-	-	-
	$Clones_{av}$	0	-	-	-	-	-
	1992 QA	8	-	-	0.73986012	-	-
	$Clones_{av}$	60	205	3	0.3550350	0.7398601	0.110918
Mars	2002 RN137	147	-	-	0.59237680	-	-
	$Clones_{av}$	184	427	36	0.5257913	0.6990184	0.354989
	2000 WN 124 0	-	-	-	-	-	
	$Clones_{av}$	69	181	2	0.5331294	0.9510737	0.251630
	1992 QA	407	-	-	0.63218410	-	-
	$Clones_{av}$	104	407	2	0.4562290	0.7512960	0.088847

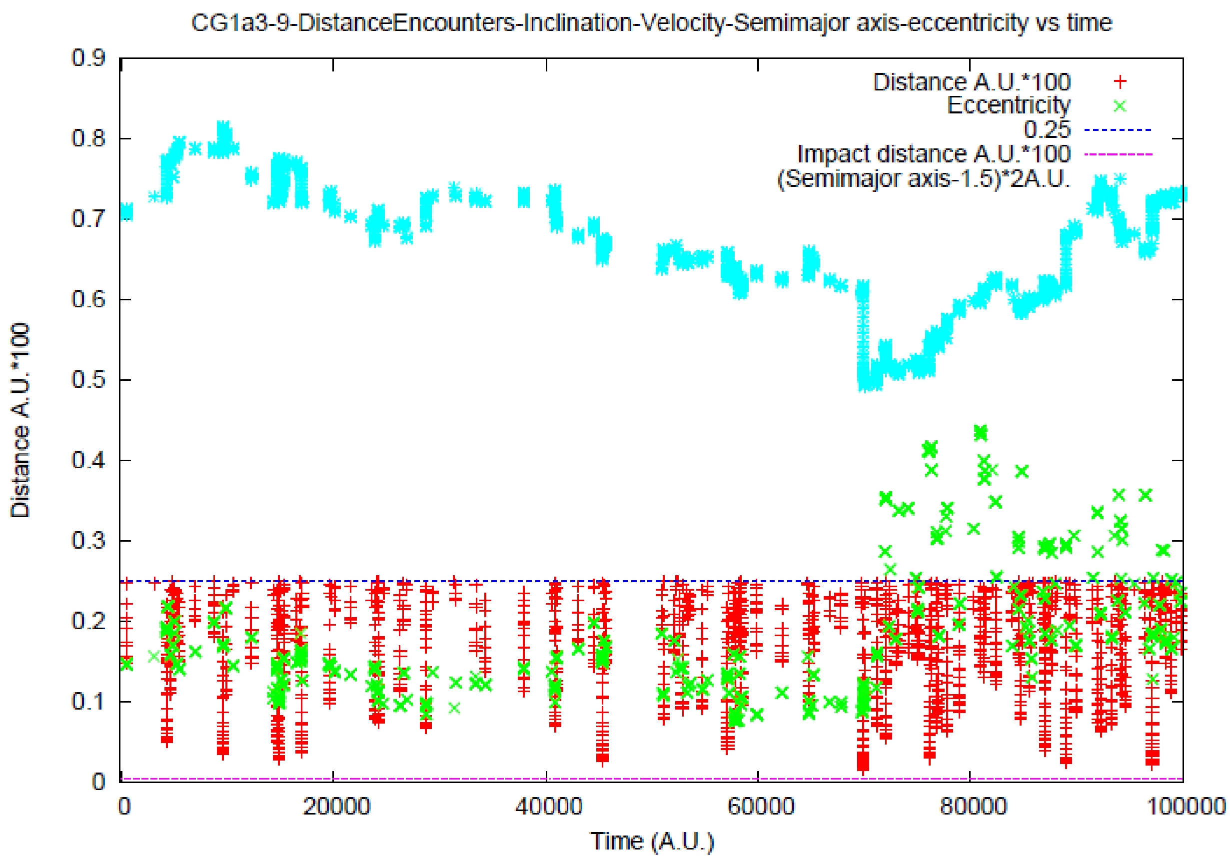
$< Enc >$=Mean number of close encouters per the clones who have a close encounter per relative planet, $MaxEnc$ =Max number of close encounter per the clones who have a close encounter per relative planet, $MinEnc$ =Min number of close encounter per the clones who have a close encounter per relative planet, $< Dur >$=Interval of time of the asteroids inside the distance of 0.0025 A.U. per relative planet, $MaxDur$ =Maximum of Dur and$MinDur$ =minimum of Dur.

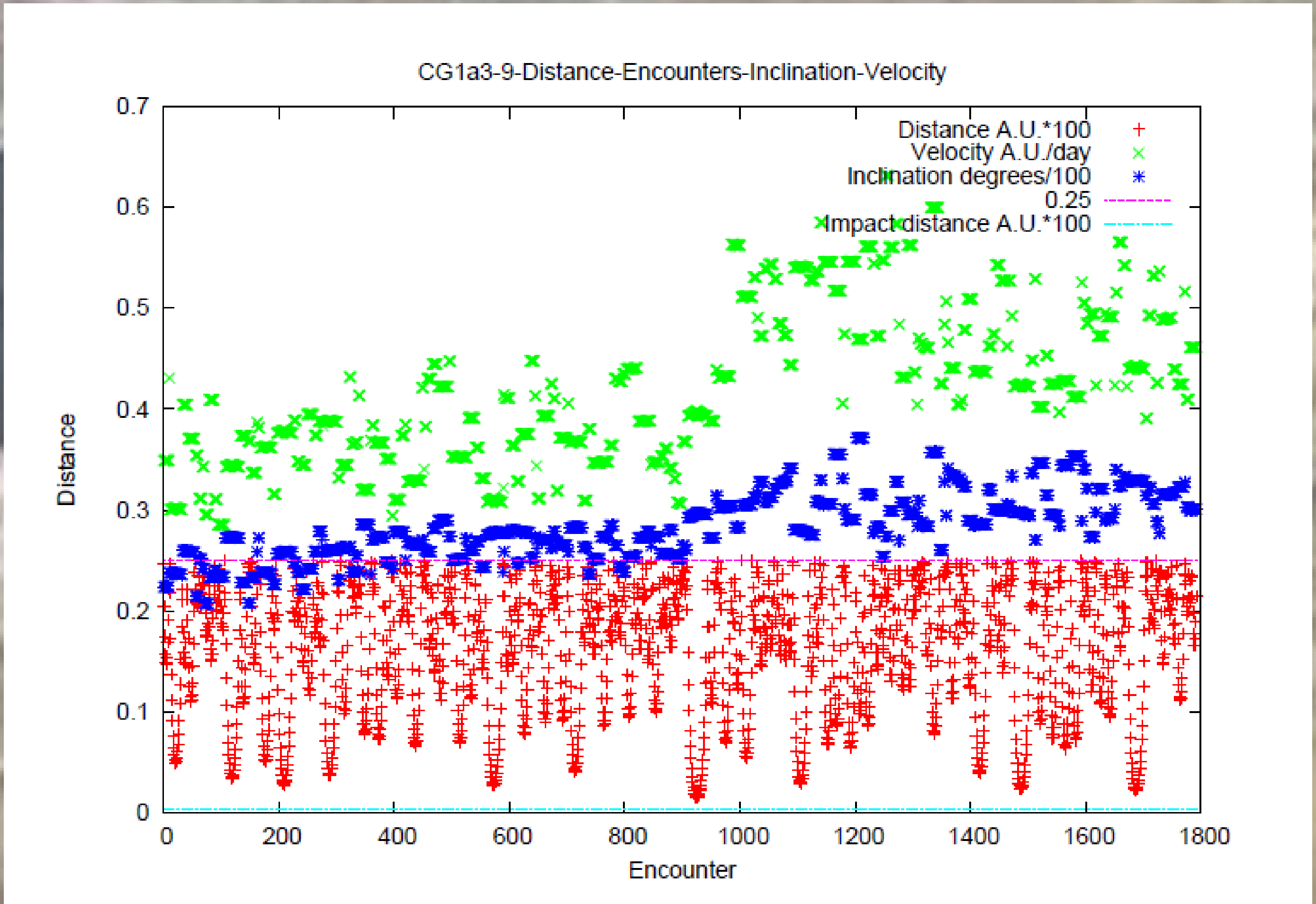
Planet	Asteroid	$<\Theta>$	$<\Theta_{max}>$	Θ_{max}	$p_{\Theta_{max}}(10^{-4})$
Earth	2002 RN137	-	-	-	-
	$Clones_{av}$	0.23	3.33	16.63	1.1245
	2000 WN 124				
	$Clones_{av}$	-	-	-	-
	1992 QA	3.37	11.48	-	5.897
	$Clones_{av}$	0.94	9.07	44.06	1.1580
Mars	2002 RN137	0.27	-	2.03	13.6000
	$Clones_{av}$	6.12	48.13	176.86	18.785
	2000 WN 124	-	-	-	-
	$Clones_{av}$	0.22	1.15	1.96	2.402
	1992 QA	0.39	-	10.47	1.490
	$Clones_{av}$	2.21	17.58	171.34	6.574

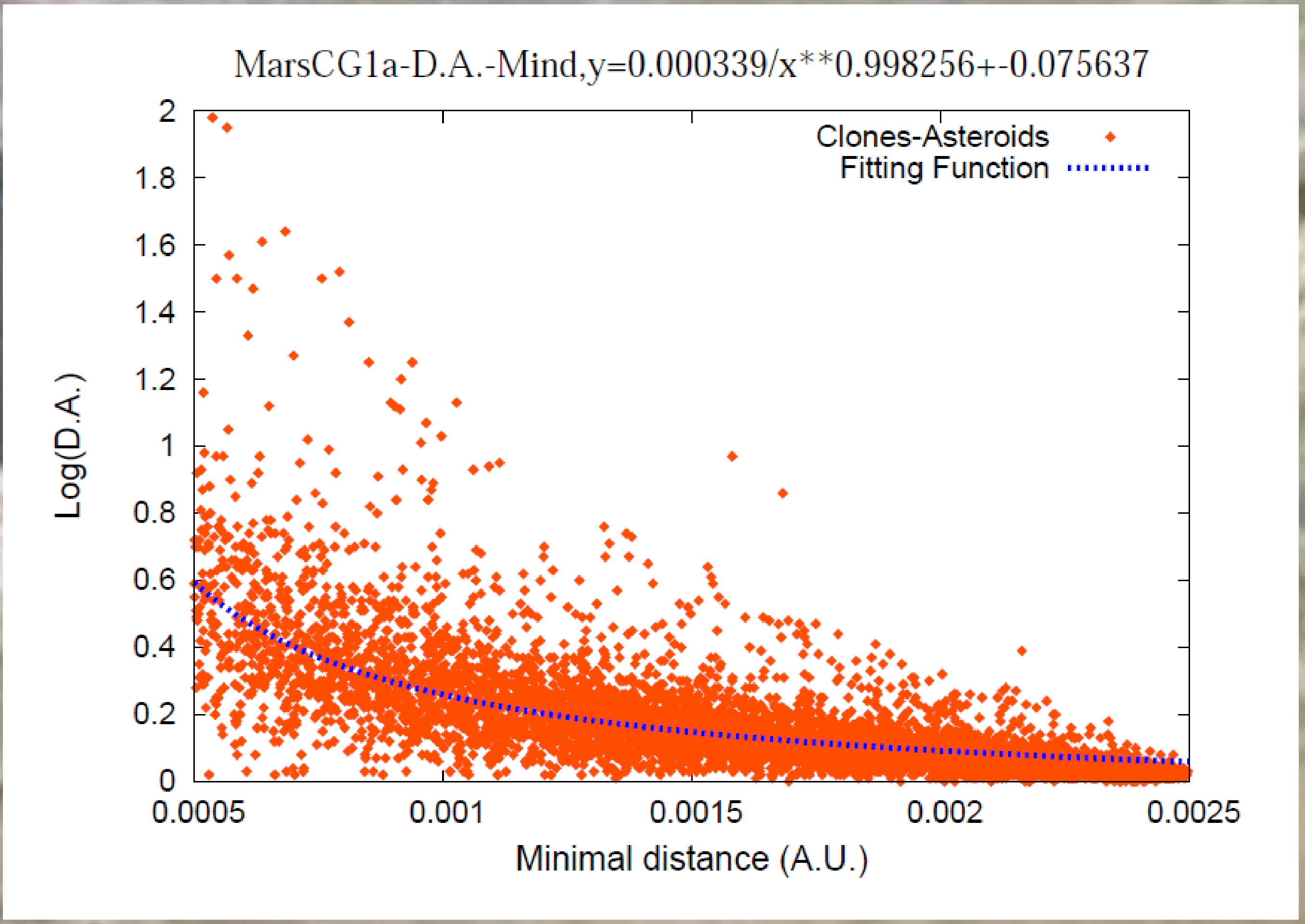
$<\Theta>$=mean angle of deflection, $<\Theta_{max}>$=Mean of the maximum of the angle of deflection, Θ_{max} =maximum angle of deflection, $p_{\Theta_{max}}(10^{-4})$ =perigeum of the close encounter at the maximum angle of deflection in 10^{-4} A.U. .


CG1a2-7-DistanceEncounters-Inclination-Velocity vs time
Distance A.U.*100
Velocity A.U./day
Inclination degrees/100
0.25
Impact distance A.U.*100
1
0.8
0.6
0.4
0.2
0
0
20000
40000
60000
80000
100000
Time (A.U.)
Distance A.U.*100

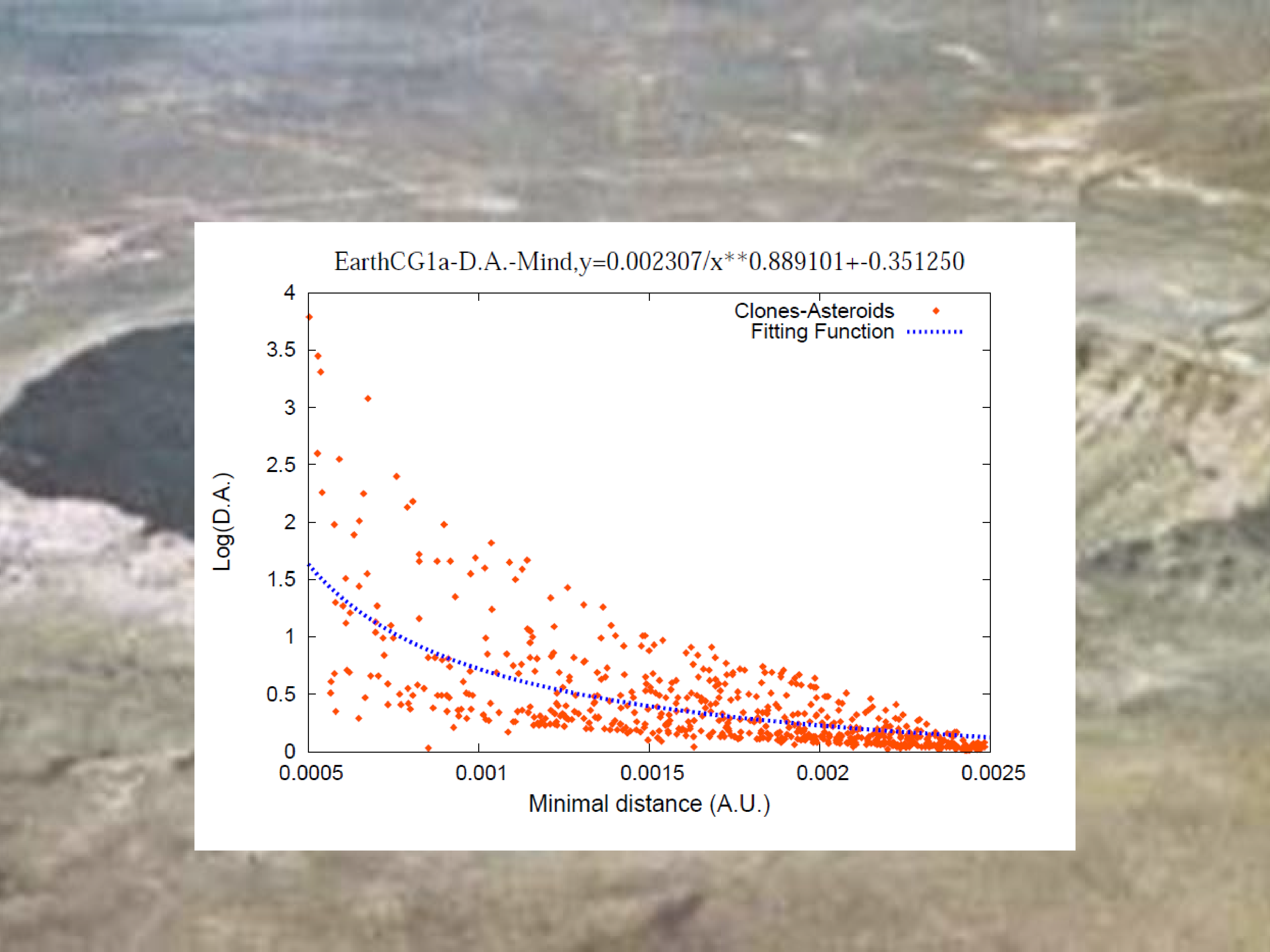

CG1a2-7-Distance-Encounters-Inclination-Velocity
Distance A.U.*100
Velocity A.U./day
Inclination degrees/100
0.25
Impact distance A.U.*100
Distance
Encounter
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350


CG1a3-9-DistanceEncounters-Inclination-Velocity-Semimajor axis-eccentricity vs time
Distance A.U.*100
Eccentricity
0.25
Impact distance A.U.*100
(Semimajor axis-1.5)*2A.U.
Distance A.U.*100
Time (A.U.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
20000
40000
60000
80000
100000


CG1a3-9-Distance-Encounters-Inclination-Velocity
Distance A.U.*100
Velocity A.U./day
Inclination degrees/100
0.25
Impact distance A.U.*100
Distance
Encounter
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
200
400
600
800
1000
1200
1400
1600
1800



MarsCG1a-D.A.-Mind,y=0.000339/x**0.998256+-0.075637
Clones-Asteroids
Fitting Function
Log(D.A.)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.0005
0.001
0.0015
0.002
0.0025
Minimal distance (A.U.)


EarthCG1a-D.A.-Mind,y=0.002307/x**0.889101+-0.351250
Clones-Asteroids
Fitting Function
Log(D.A.)
4
3.5
3
2.5
2
1.5
1
0.5
0
0.0005
0.001
0.0015
0.002
0.0025
Minimal distance (A.U.)

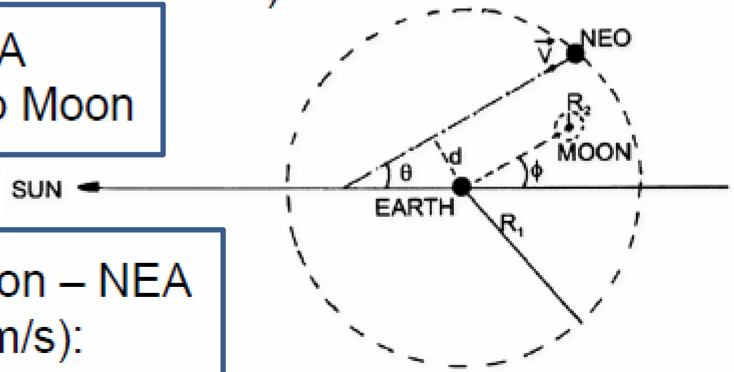
About NEAs & the Moon

- Known facts
  - NEAs as the major source for impact craters in past 3 Ga
  - Continuous replenishment from MBA
  - Time scale to become Earth crosser $\leq 10^6$ yr
  - Dynamical lifetime in NEO region $\leq 10^7$ yr

(from: Morbidelli, Bottke, Froeschlé, Michel, 2002)

- Domingos, Winter & Neto (2004)
  - assessment of Moon's contribution on impacts on Earth
  - comparison of two models (planar cases)

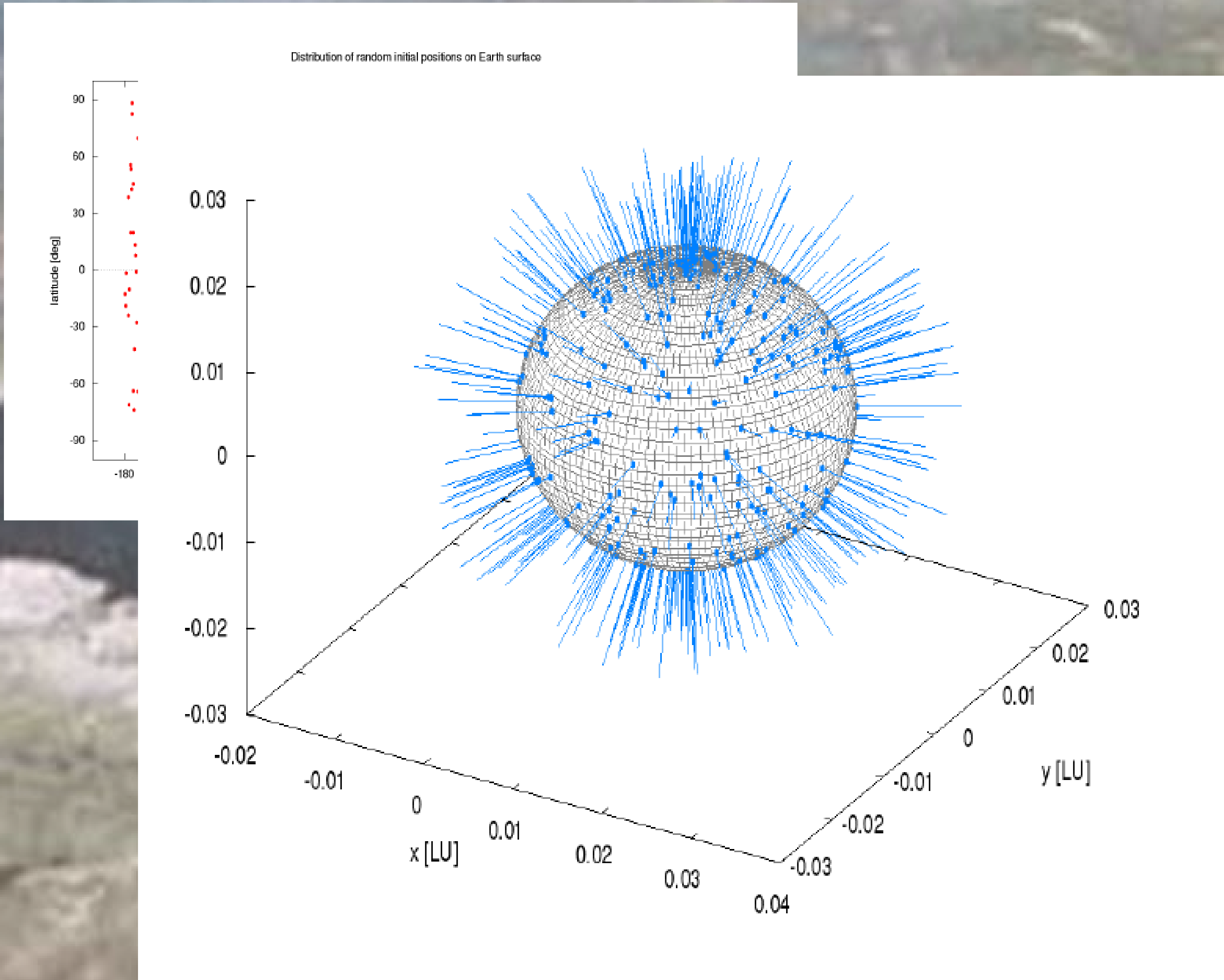
- model 1 = Sun – Earth – NEA
  sample of collision orbits w/o Moon

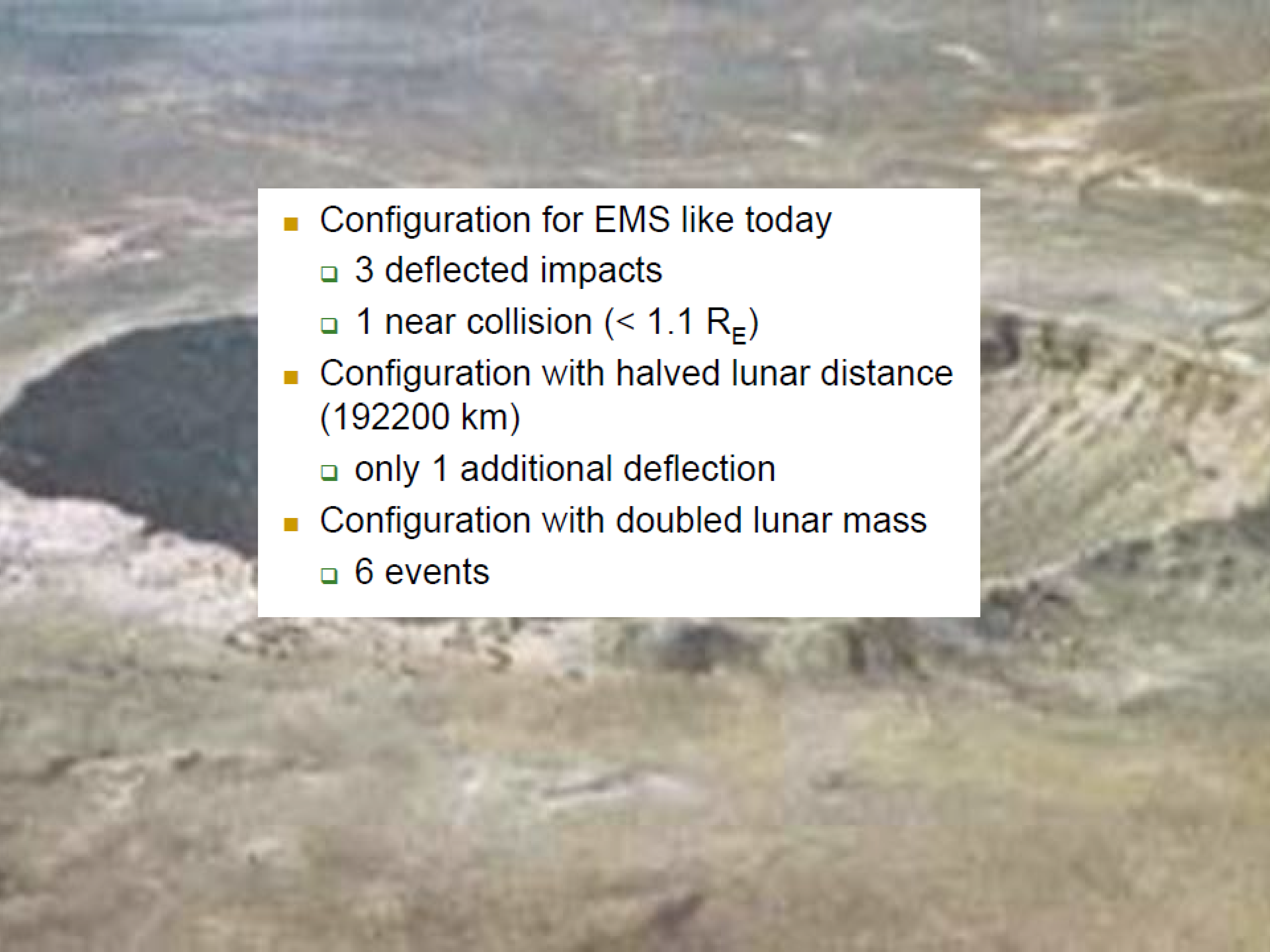


- model 2 = Sun – Earth – Moon – NEA
  low relative velocities (≤ 5 km/s):
  Moon on average deflects 2.6%
  of NEAs on collision trajectories

- 3D CR3BP Earth – Moon – NEA
- rotating barycentric coordinate system
  (Szebehely, 1967)
- normalized units
  - $G = 1$, $M = 1$
  - length unit LU = 384400 km
  - time unit TU = 4.37 d
  - mass parameter $\mu = 1/82.30057$

- Starting on Earth surface
- Uniform random distribution of “impact sites”
  - velocity in range $1 < v/v_{esc} < 2$
  - normal to surface
- Phase 1: no Moon – follow orbit until outside Sphere of Influence (SOI) of 150 R_E
- Phase 2: add Moon & reverse time direction – impact still taking place?
- 30000 initial conditions


Distribution of random initial positions on Earth surface
90
60
30
0
-30
-60
-90
latitude [deg]
-180
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
x [LU]
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
y [LU]



- Configuration for EMS like today
  - 3 deflected impacts
  - 1 near collision (< 1.1 R_E)
- Configuration with halved lunar distance (192200 km)
  - only 1 additional deflection
- Configuration with doubled lunar mass
  - 6 events


EPILOG

Symmetric Lie Series Integration?

...take a step forward...

$$\vec{z}_{n+1} = e^{\tau D}\vec{z}_n$$

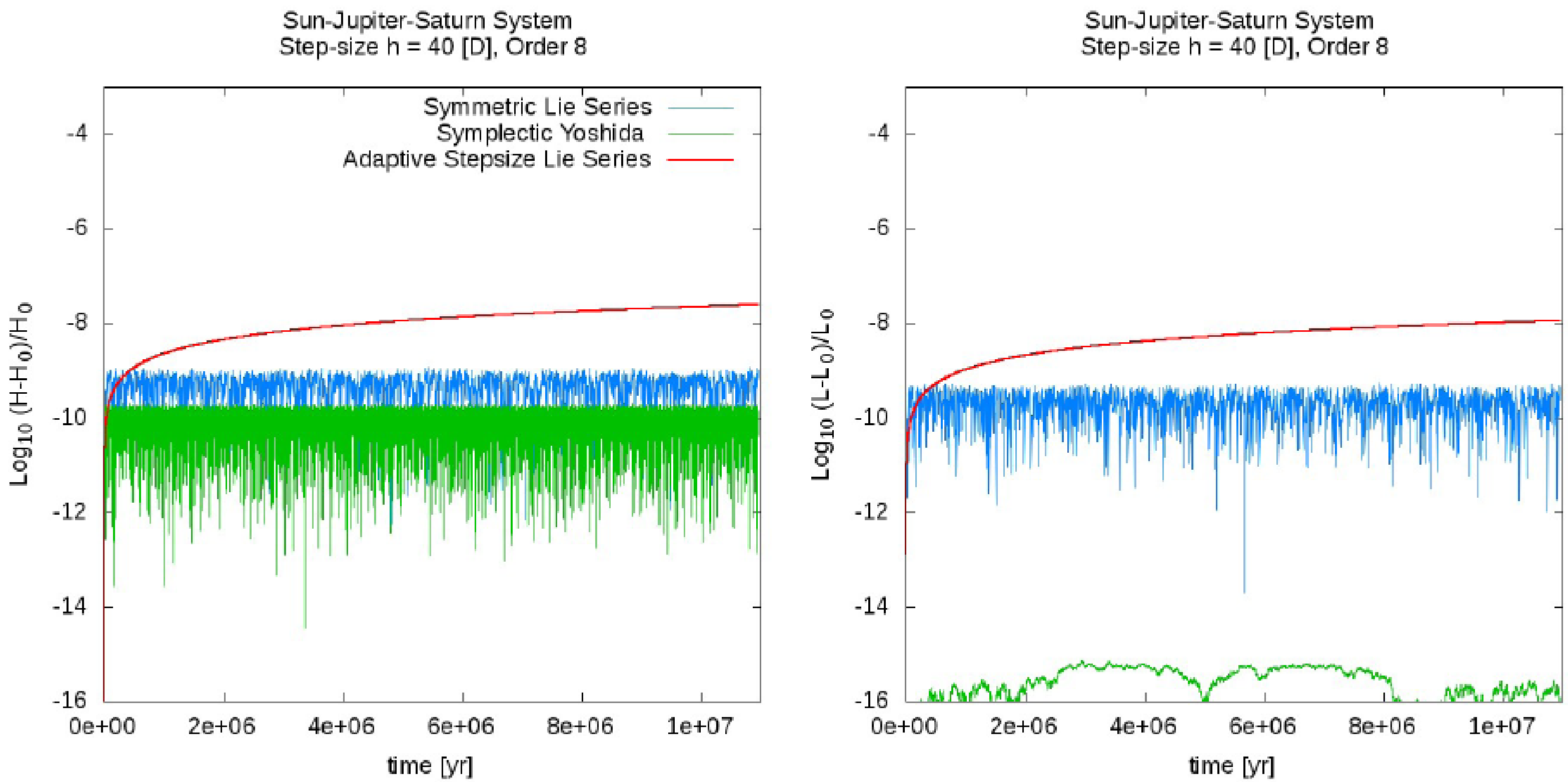
...take a step back...

$$\vec{z}_{n-1} = e^{-\tau D}\vec{z}_n$$

...a symmetric two step method

$$\vec{z}_{n+1} = 2\sum_{m=0}^{O} \frac{(\tau D)^{2m}}{(2m)!}\left[\vec{z}_n + \vec{z}_{n-1}\right]$$

where $O \in \mathbb{N}_{+,even}$ is the order of truncation of the symmetric Lie Series algorithm.



Sun-Jupiter-Saturn System
Step-size h = 40 [D], Order 8
Symmetric Lie Series
Symplectic Yoshida
Adaptive Stepsize Lie Series
Log_{10} (H-H_0)/H_0
-4
-6
-8
-10
-12
-14
-16
0e+00
2e+06
4e+06
6e+06
8e+06
1e+07
time [yr]
Sun-Jupiter-Saturn System
Step-size h = 40 [D], Order 8
Log_{10} (L-L_0)/L_0
-4
-6
-8
-10
-12
-14
-16
0e+00
2e+06
4e+06
6e+06
8e+06
1e+07
time [yr]

Order	Yoshida	Symmetric Lie Series
6	8	6
8	16	8
10	32	10

relative CPU-Time for Sun-Jup-Sat, $t = 10^7$ [yrs], Order 8:

Symmetric Lie Series	Yoshida	Adaptive Stepsize Lie Series
1	2	2.8

Dans notre groupe ADG a Vienne on travaille sur les trois aspects

-> Construire un integrateur qui est precis et rapid

-> La contribution des familles des Asteroides (Hungarias, Flora et Themis) pour le NEAs et determiner les collisions avec la terre

-> Examiner le role de la Lune


MERCI! THANK YOU!