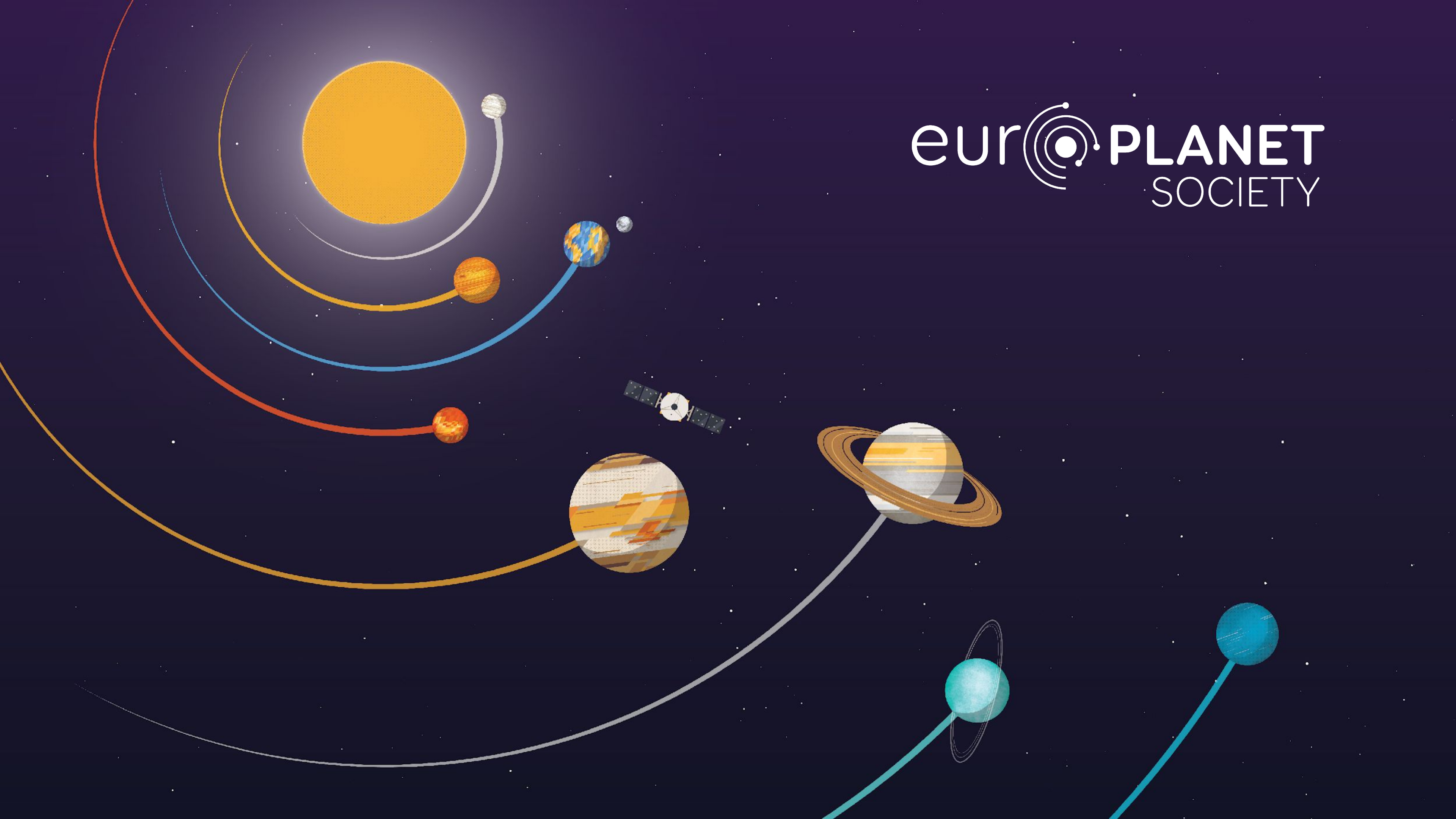
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# An earth-grazing fireball case: simulating close encounters using Rebound Python package and a 4th order Sympletic Integrator

Observatório Nacional

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**Astronomical Institute of the Romanian Academy**

Seminars

04 July 2023
Bucharest

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# INTRODUCTION

**Bolides and Meteors**

**Video registration: Exoss project**

**Grazing meteors**

**Case: 1990 October 13th an Earth grazing fireball**

- ***methodology***
- ***results***

**Numerical Integration : a case study**

- **simulations**
- **results**

**Conclusion**

# MOTIVATION

An Earth-grazing meteoroid will graze one more time the Earth? How many times, until collides with Earth? Can we model that with after-orbit?
Backwards with a before-orbit, can we integrate if it had a close encounter with Earth?

# INTRODUCTION

**Meteoroid** : from 10 μm  1 meter ( Borovicka J., Asteroids, Comets, Meteors, 2005)

**Meteor**:  light associated to physical phenomena, from the high speed entry of a solid object into atmosphere (Roggemans,  JIMO 1987)

**Meteorite**: natural solid that survived meteor phase . (Roggemans, JIMO 1987)


# METEOR ORIGINS

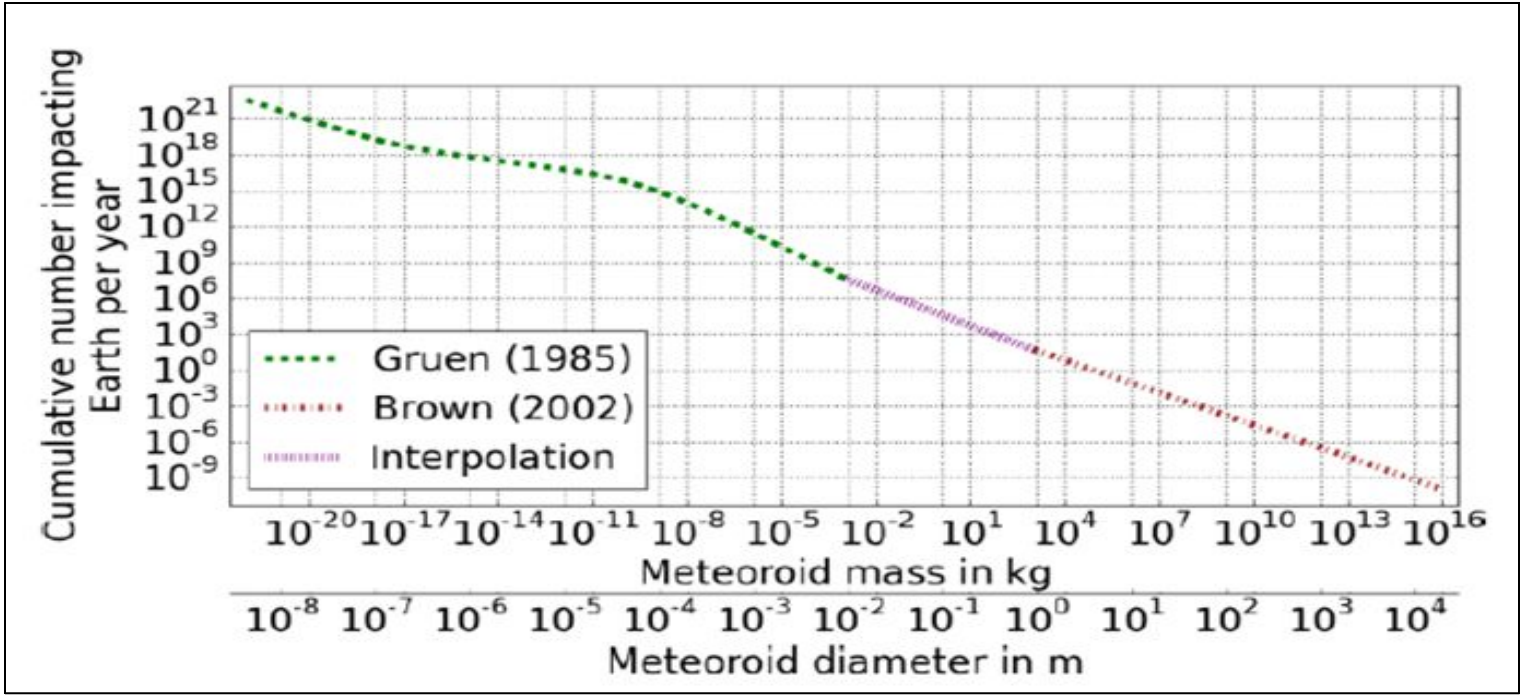
NEAS, Asteroids – MB, Comet debris. In small basis from Moon and Mars debris and interestellar medium.
(Borovicka, 2005, Jopek, 2011)


# MASS FLUX HITTING EARTH

2 models:

(a) Grüen

(b) Brown

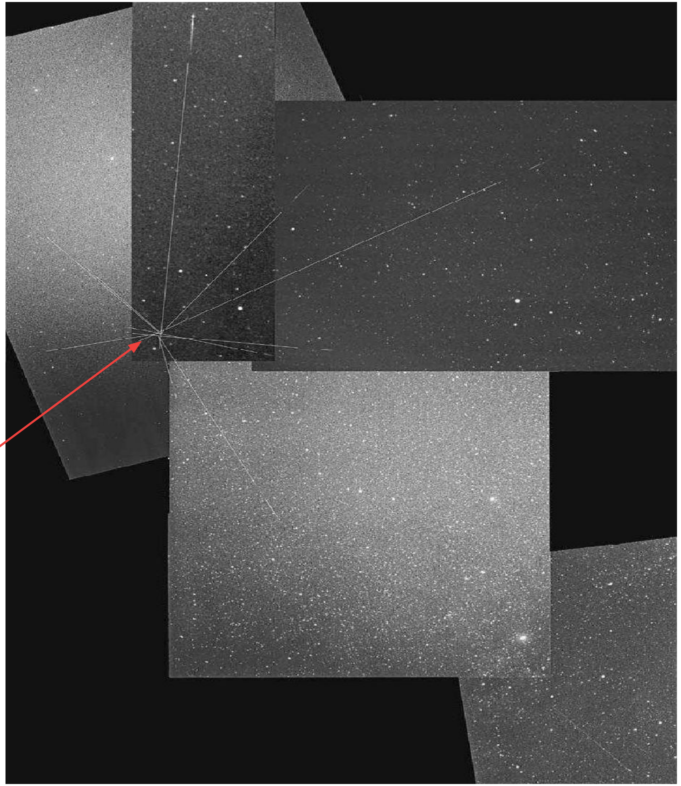


# METEORS : SHOWERS

**Showers**

Meteoroids fluxs, similar orbits and parallel trajectory, (Roggemans, JIMO 1987)

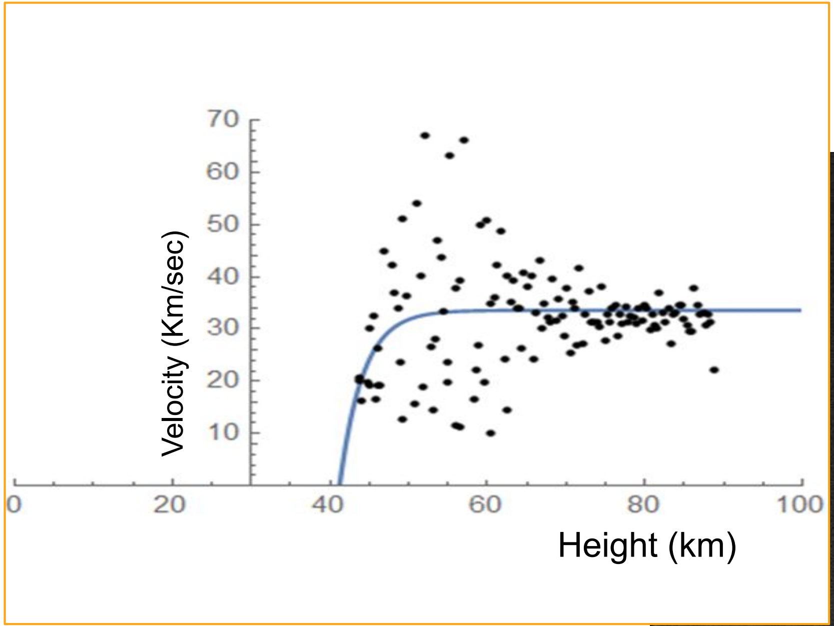
An apparent geometric point in the sky.



# SCIENTIFIC GOALS

- ❑ Detect and inferer the flux total of debris crossing Earth-Moon system.
- ❑ Survey of possible impactors, as long period comets
- ❑ Low cost way to study Asteroidal/NEO materials

# METEORS PHYSICAL PROPERTIES




# METEORS PHYSICAL PROPERTIES

Light curves, velocities and heights→ ***mass and density***. (Jopek & Williams, 2013)

$$dV/dt = -\Gamma A \rho_m^{-2/3} \rho m^{-1/3} V^2 \quad (1)$$

$$dm/dt = (-\Lambda A/2\zeta) \rho_m^{-2/3} \rho m^{2/3} V^3 \quad (2)$$

$$dh/dt = -V \cos Z_R \quad (3)$$

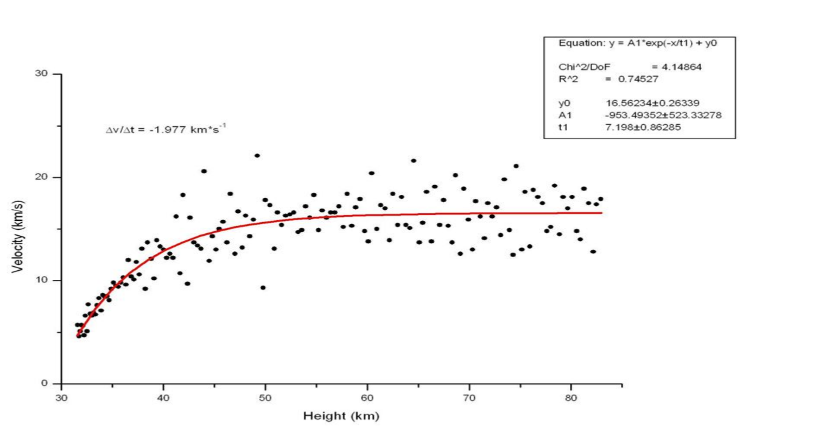
$$I = -(\tau/2)(dm/dt) V^2 \quad (4)$$

where

- $V$ velocity;
- $\Gamma$ drag coefficient;
- $A$ shape factor;
- $\rho_m$ bulk density of the meteoroid;
- $\rho$ atmospheric density;
- $m$ mass of the meteoroid;
- $\Lambda$ heat transfer coefficient;
- $\zeta$ energy of ablation;
- $h$ height above sea level;
- $Z_R$ zenith distance of the meteor radiant;
- $I$ luminosity;
- $M$ meteor magnitude equals $-2.5 \log I$;
- $\tau$ luminous efficiency.

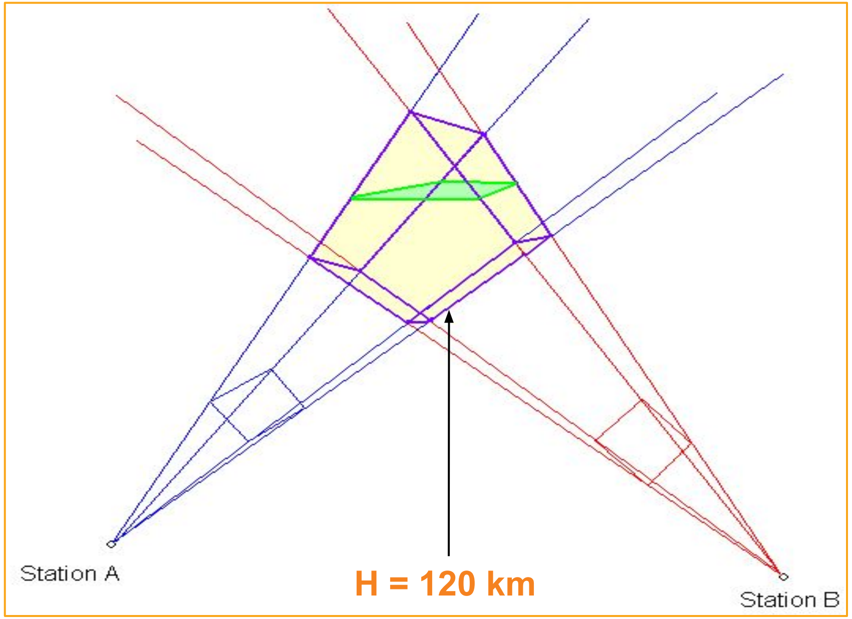
Classical Equations ***single body non-frag.***

***fittings*** for getting parameters modeling physical characteristics



# METEORS MONITORING

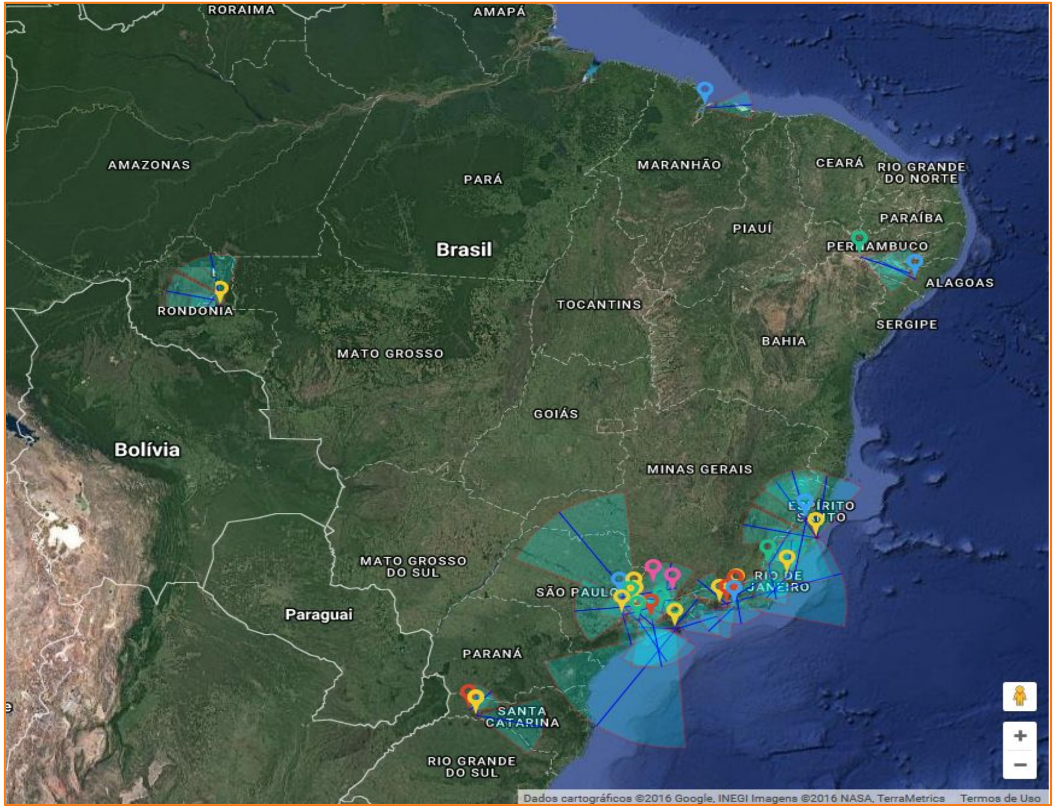
Meteor triangulation



# THE BRAZILIAN VIDEO MONITORING METEORS NETWORK EXOSS: STATUS

# OBSERVATIONAL NETWORK

32 members
55 cameras
Source: exoss.org



# FIREBALLS AND REENTRIES

NA MOSCA

## Julio Lobo acertou sobre a explicação para luzes no céu

Autoridade astronômica confirmou que fenômeno foi causado por lixo espacial

Israel Moreira
israel.moreira@rac.com.br

As luzes que foram vistas no céu de Campinas e de outras cidades da região na noite de segunda-feira eram, na verdade, detritos de um foguete chinês, conhecidos como lixo espacial. Essa conclusão foi confirmada pela Saipher ATC, empresa responsável pelo desenvolvimento do Horus (Sistema Holístico de Redução de Risco e Incerteza), que monitora e analisa os riscos espaciais na atmosfera.

Após uma investigação mais aprofundada, foi possível descobrir que o objeto em questão era um fragmento de um foguete chamado Chang Zheng 2C. Nesse caso específico, o estágio do foguete perdeu altitude mais rapidamente do que o esperado, resultando em sua reentrada na atmosfera terrestre antes do previsto.

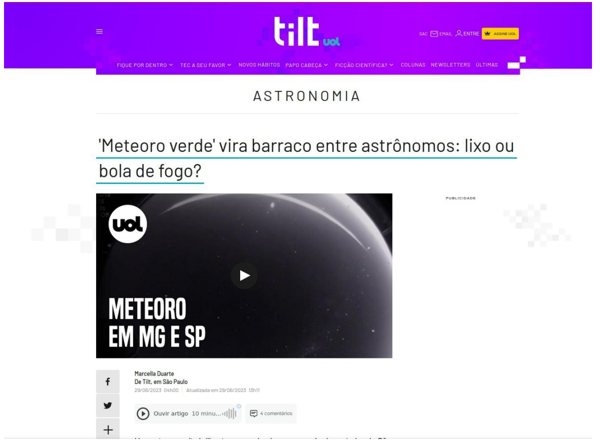
"Com aproximadamente 35 metros de altura e um diâmetro de 3,35 metros, o Chang Zheng 2C é capaz de transportar cargas úteis de até 2 toneladas. Ele faz parte da família de foguetes Longa Marcha, desenvolvida pela China Academy of Launch Vehicle Technology (CALT), e tem sido utilizado para diversos fins, como comunicações, observação da Terra, pesquisa científica e experimentos tecnológicos. Sua confiabilidade e eficiência o tornam uma ferramenta importante para o programa espacial chinês", explica Matheus Felipe Pacheco, analista de Sistemas Espaciais.

O astrônomo Julio Lobo, do Observatório Municipal de Campinas Jean Nicolini, com 40 anos de experiência em observações do céu, já havia confirmado à reportagem do Correio Popular na segunda-feira que as características visuais do objeto luminoso correspondiam a lixo espacial, ou seja, restos de um foguete. "O saldo positivo de toda essa história foram os debates entre os especialistas, que levaram à reflexão e análise de um evento raro no Brasil. Isso é fundamental para promover discussões sobre meteoros ou lixo espacial", confirma Lobo.

Segundo José Vagner Vital, Diretor de Inovação e Novos Negócios e veterano da Saipher ATC, a missão da empresa é fornecer ferramentas de Consciência Situacional no Ambiente Espacial e no Domínio Espacial de Combate para operadores de sistemas espaciais civis e militares. A empresa conseguiu realizar a identificação das luzes avistadas.

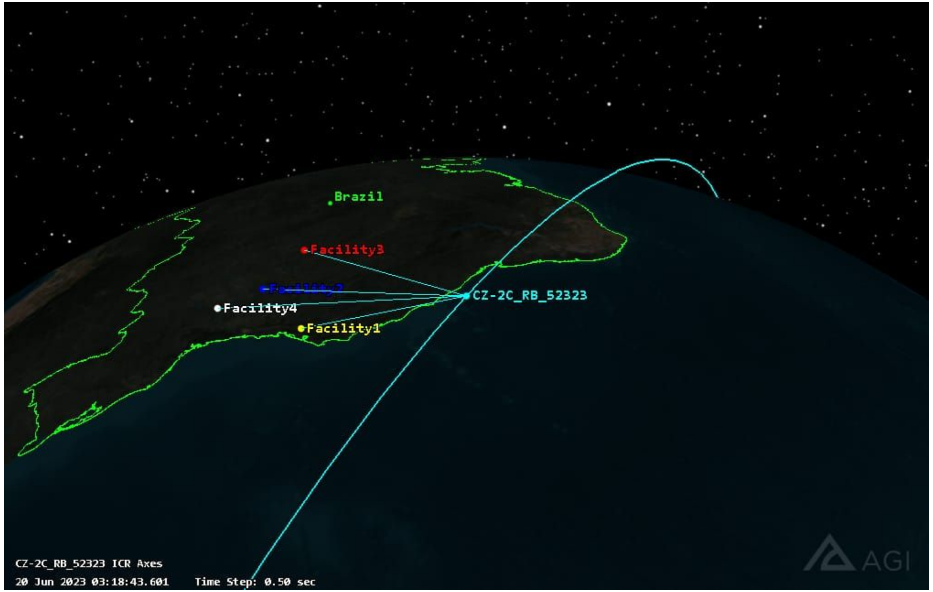
19/06/2023
18:46 hs BR local time

"Julio Lobo Nailed the Explanation for the Lights in the Sky"




"Green Meteor Sparks Debate Amongst Astronomers: Space Debris or Fireball?"

# FIREBALLS AND REENTRANCIES




"Just space junk!!"

- Saipher, technical report 21/06/2023.

# EARTH GRAZING METEORS

## EARTH-GRAZING FIREBALL'S RECURRENCE

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[3]*Exoss project, press.org.exoss*
[4]*Astronomical Institute of the Romanian Academy*
*Astronomical Observatory of Cluj-Napoca*
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*Abstract.* Grazing meteors type is meteoroid debris that enters the planetary atmosphere with a near-horizontal path and perigee very high to the ground, having only part of their material being ablated during air interaction so the remaining could return to space at a different orbit after that brief encounter. On October 13, 1990, an Earth-grazing fireball crossed the atmosphere, with an absolute magnitude of $-6$ and lasting 10 seconds, with an initial velocity of 41.7 $\mathrm{km \cdot s^{-1}}$. It was observed above Czechoslovakia and Poland and registered by two Czech stations of the European Fireball Network. The bolide travelled about 409 km during its luminous trajectory. The modified orbit of the remaining material was calculated using the specific method for long trajectory determination by the authors Borovicka and Ceplecha (1992). Using REBOUND's Python package, we implemented calculations for that grazing type close encounters back and forth in time, before initial conditions (IC) used for the retrograde integration and the after IC for prograde integration, then the same steps were done running the equation of motions under a fourth order Symplectic Integrator. Both results were compared in order to find out if we can obtain a capture (or a collision) in time (back or forth) simulating the Solar System. Finally, a forward and backward propagation in time of the meteoroid is presented using the described equations of motion and fourth-order symplectic Neri integrator.

*Key words*: Celestial Mechanics – Meteors – Orbit determination – Numerical integration.

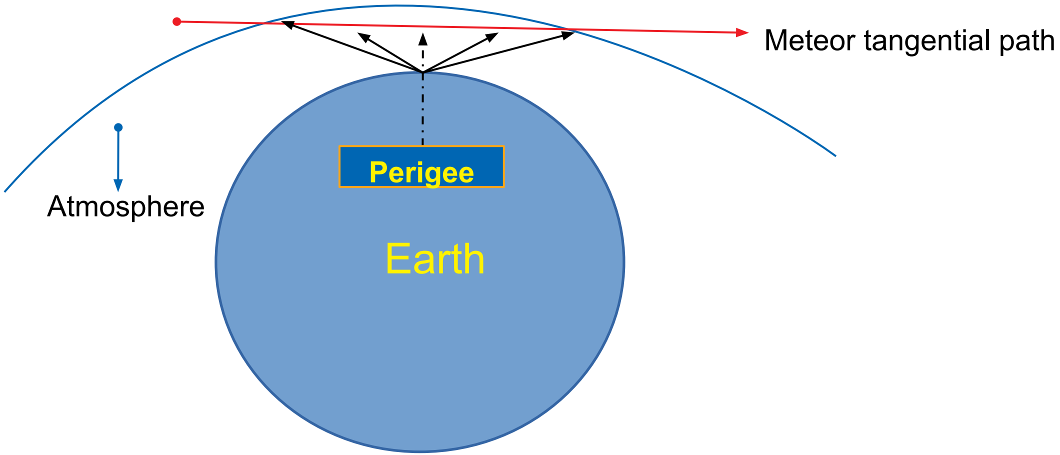
Romanian Astron. J. , Vol. 32, No. 3, p. 175–194, Bucharest, 2022

# EARTH GRAZING METEORS: WHAT IS IT ?

Grazing meteors are phenomena which occur when meteoroid debris from comets or asteroids that enter the planetary atmosphere with a near-horizontal path and perigee very high to the ground, having only part of their material being ablated during air interaction so the remaining might return to space at a different orbit after that brief close encounter (De Cicco & SZUCS-CSILLIK, 2023)

# EARTH GRAZING METEORS: WHAT IS IT ?

Grazing meteors are phenomena which occur when meteoroid debris from comets or asteroids that enter the planetary atmosphere with a near-horizontal path and perigee very high to the ground, having only part of their material being ablated during air interaction so the remaining might return to space at a different orbit after that brief close encounter (De Cicco & SZUCS-CSILLIK, 2023)



# HISTORICAL REGISTERING

1784 : “The Great Meteor” was observed, moving in a path more than 160 km.

1860 : another grazing was observed (Olson et al., 2010).

1912: the “Great Meteor procession” crossed North and South America continents (Chant, 1913; Denning, 1916).

1972: On August 10, 1972, a daylight Earth-grazing fireball crossed the United States and Canada, registered photographically (Ceplecha, 1979).

1990: On October 13, 1990, grazing fireball crossing East Europe (Borovicka and Ceplecha, 1992).

1992: On October 1992, Meteorite Peekskill, over the eastern United States (Ceplecha et al., 1996).

2003: On 2003, Ukraine grazing meteor (Kozak and Watanabe, 2017).

2006: On March 29, 2006, a grazing over Japan (Abe et al., 2006).

2007: On August 27, 2007, the grazing was observed by the European Fireball Network (Spurný et al., 2008).

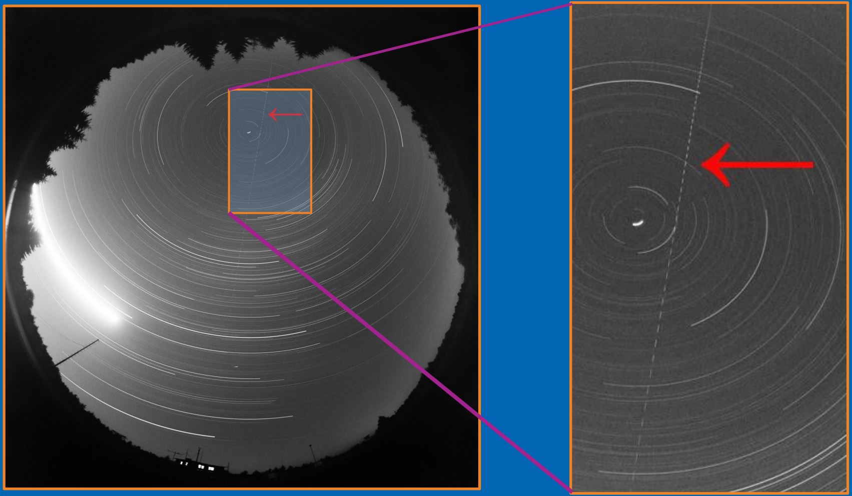
2012: On June 10, 2012, the first grazing associated with a meteor shower in the scientific literature, daytime ρ - Perseids shower (Madiedo et al., 2016).

2013: On March 31, 2013, a grazing meteor over Germany and Austria (Oberst et al., 2014).

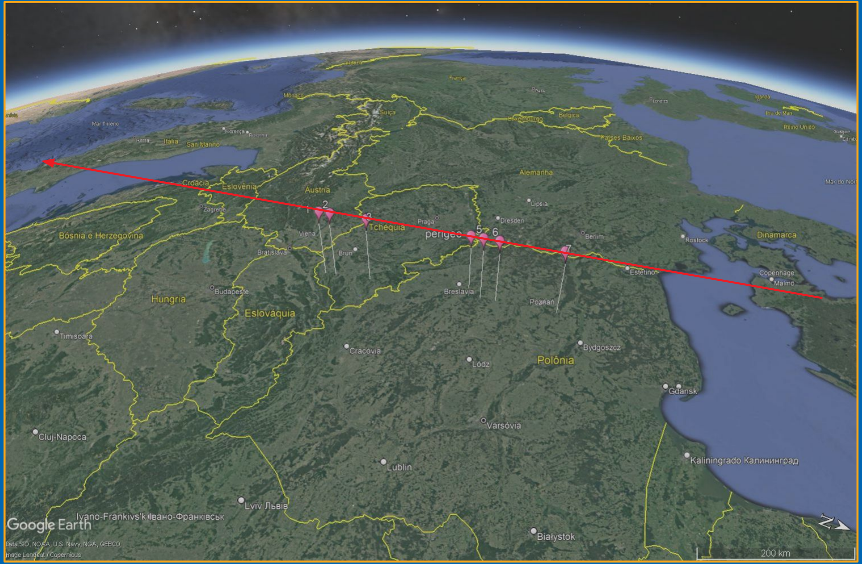
2014:On December 24, 2014, a grazing fireball over Algeria, Spain and Portugal (Moreno et al., 2016).

2017: July 7, 2017, the Desert Fireball Network observed a grazing fireball that travelled over 1300 km through the atmosphere above Western Australia and South Australia (Shober et al., 2020).

# GRAZING FIREBALL CROSSING EAST EUROPE : 03/10/1990



https://www.wikidata.org/wiki/Q19280175




Borovicka and Ceplecha,1992

# GRAZING FIREBALL CROSSING EAST EUROPE : 03/10/1990

13-10-1990: 03:27:16 UT

*3 indtp observations : Czecholosvakia – EFN*

*N-S direction*

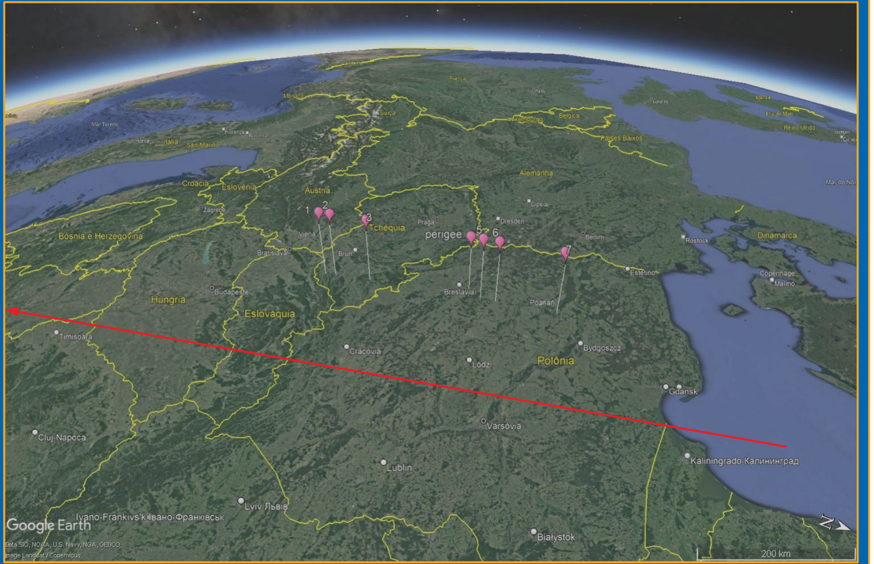
(a) *Luminous trajectory → 409 km @ 9.8 secs and* $Veloc_i$ *= 41.7 km/sec*

(b) *Initial mass: 44 kg, ablated ~ 0.35 kg*

(c) *Average absoulute mag: -6.25 @ maximum – perigee point.*

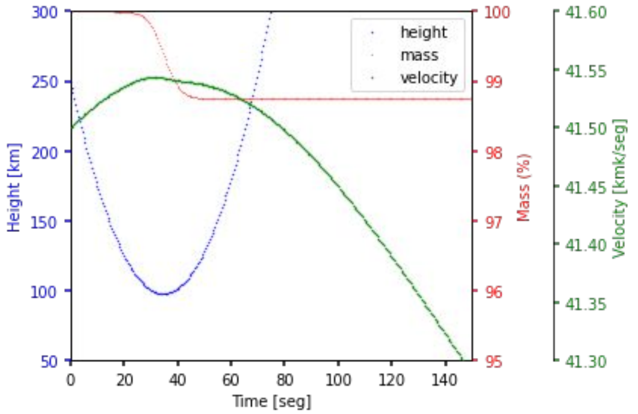
(d) *Ceplecha's classif.: Tipe I – stony (fireball meteorite-dropping type),*

**Back deep space as a meteorite type with fusion crust !**



# EARTH-GRAZING FIREBALL: *COMPUTATIONAL SIMULATION*

| Time (seg) | GTrack (Km) | Height (Km) | Velocity (km/seg) | Decel (m/s^2) | Mass (%) | Visual (Mag) |
|---|---|---|---|---|---|---|
| 0.000 | 0.00 | 250.00 | 41.500 | 0.000 | 100.000 | .65 |
| 5.000 | 196.41 | 209.57 | 41.511 | 0.000 | 100.000 | 3.85 |
| 10.00 | 395.08 | 175.23 | 41.520 | 0.001 | 100.000 | 2.26 |
| 15.00 | 595.68 | 147.09 | 41.528 | 0.003 | 99.998 | 0.74 |
| 20.00 | 797.84 | 125.23 | 41.535 | 0.017 | 99.994 | -1.52 |
| 25.00 | 1001.18 | 109.71 | 41.541 | 0.110 | 99.965 | -3.87 |
| *30.00* | *1205.31* | *100.59* | *41.543* | *0.479* | *99.798* | *-5.65* |
| *35.00* | *1409.83* | *97.89* | *41.543* | *0.798* | *99.358* | *-6.26* |
| *40.00* | *1614.32* | *101.61* | *41.541* | *0.407* | *8.934* | *-5.45* |
| 45.00 | 1818.38 | 111.76 | 41.539 | 0.082 | 98.781 | -3.5 |
| 50.00 | 2021.62 | 128.29 | 41.537 | 0.013 | 98.756 | -1.19 |
| 55.00 | 2223.65 | 151.17 | 41.534 | 0.002 | 98.751 | 1.11 |
| 60.00 | 2424.09 | 180.33 | 41.529 | 0.001 | 98.750 | 2.51 |
| 65.00 | 2622.58 | 215.68 | 41.523 | 0.000 | 98.750 | 4.14 |
| 70.00 | 2818.80 | 257.13 | 41.516 | 0.000 | 98.750 | 5.97 |



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| 10.00 | 395.08 | 175.23 | 41.520 | 0.001 | 100.000 | 2.26 |
| 15.00 | 595.68 | 147.09 | 41.528 | 0.003 | 99.998 | 0.74 |
| 20.00 | 797.84 | 125.23 | 41.535 | 0.017 | 99.994 | -1.52 |
| 25.00 | 1001.18 | 109.71 | 41.541 | 0.110 | 99.965 | -3.87 |
| ***30.00*** | ***1205.31*** | ***100.59*** | ***41.543*** | ***0.479*** | ***99.798*** | ***-5.65*** |
| ***35.00*** | ***1409.83*** | ***97.89*** | ***41.543*** | ***0.798*** | ***99.358*** | ***-6.26*** |
| ***40.00*** | ***1614.32*** | ***101.61*** | ***41.541*** | ***0.407*** | ***8.934*** | ***-5.45*** |
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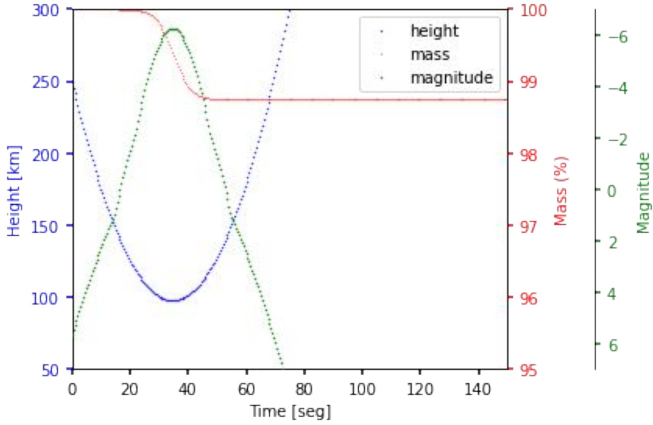
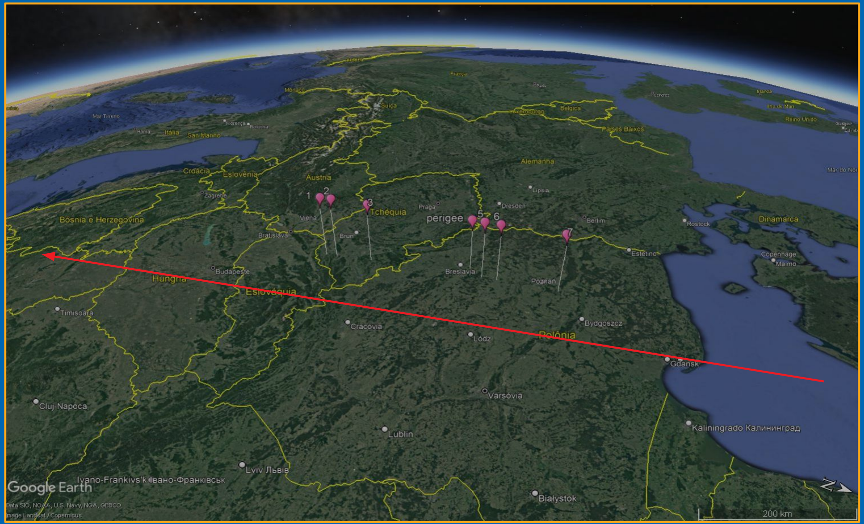


# EARTH-GRAZING FIREBALL: *ORBITAL ELEMENTS*

| | before encounter | after encounter |
|---|---|---|
| $\alpha_G$ | $97^{\circ}.27 \pm 0^{\circ}.01$ | $96^{\circ}.84 \pm 0^{\circ}.01$ |
| $\delta_G$ | $-40^{\circ}.55 \pm 0^{\circ}.01$ | $-36^{\circ}.31 \pm 0^{\circ}.01$ |
| $v_G$ | $40.22 \pm 0.17$ km/s | $40.22 \pm 0.17$ km/s |
| $a$ | $2.72 \pm 0.08$ A.U. | $1.87 \pm 0.03$ A.U. |
| $P$ | $4.5 \pm 0.2$ yr | $2.56 \pm 0.06$ yr |
| $e$ | $0.64 \pm 0.01$ | $0.473 \pm 0.009$ |
| $q$ | $0.9923 \pm 0.0001$ A.U. | $0.9844 \pm 0.0002$ A.U. |
| $Q$ | $4.45 \pm 0.15$ A.U. | $2.76 \pm 0.07$ A.U. |
| $\omega$ | $9^{\circ}.6 \pm 0^{\circ}.1$ | $16^{\circ}.6 \pm 0^{\circ}.2$ |
| $\Omega$ | $18^{\circ}.973$ | $18^{\circ}.973$ |
| $i$ | $71^{\circ}.4 \pm 0^{\circ}.2$ | $74^{\circ}.4 \pm 0^{\circ}.2$ |

(Borovicka and Ceplecha, 1992)

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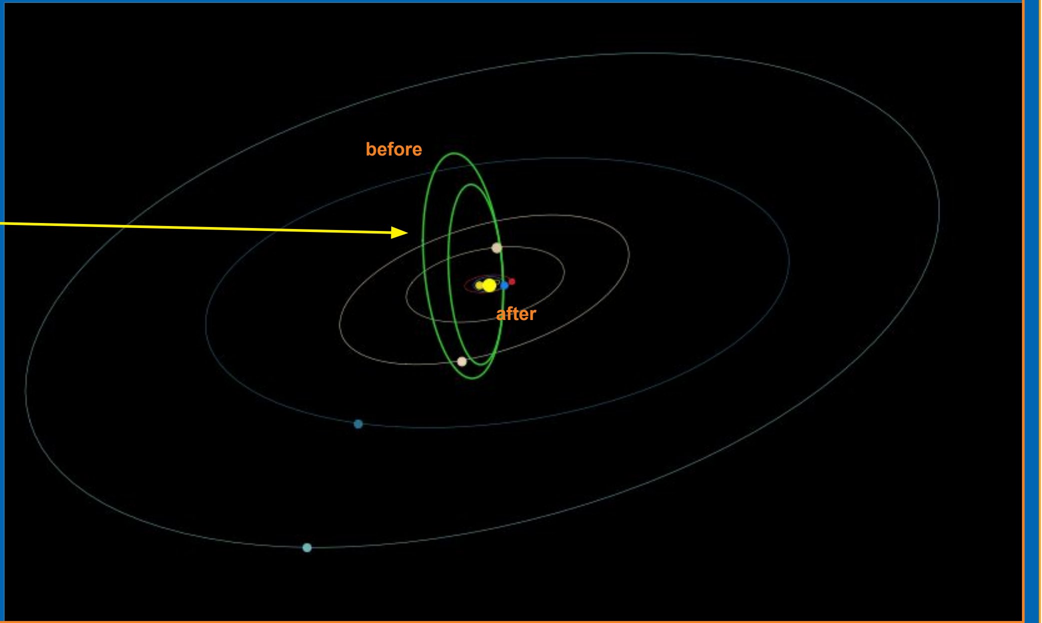
# EARTH-GRAZING FIREBALL: *ORBITAL ELEMENTS*

| | before encounter | after encounter |
|---|---|---|
| $\alpha_G$ | 97°.27 ± 0°.01 | 96°.84 ± 0°.01 |
| $\delta_G$ | −40°.55 ± 0°.01 | −36°.31 ± 0°.01 |
| $v_G$ | 40.22 ± 0.17 km/s | 40.22 ± 0.17 km/s |
| $a$ | 2.72 ± 0.08 A.U. | 1.87 ± 0.03 A.U. |
| $P$ | 4.5 ± 0.2 yr | 2.56 ± 0.06 yr |
| $e$ | 0.64 ± 0.01 | 0.473 ± 0.009 |
| $q$ | 0.9923 ± 0.0001 A.U. | 0.9844 ± 0.0002 A.U. |
| $Q$ | 4.45 ± 0.15 A.U. | 2.76 ± 0.07 A.U. |
| $\omega$ | 9°.6 ± 0°.1 | 16°.6 ± 0°.2 |
| $\Omega$ | 18°.973 | 18°.973 |
| $i$ | 71°.4 ± 0°.2 | 74°.4 ± 0°.2 |

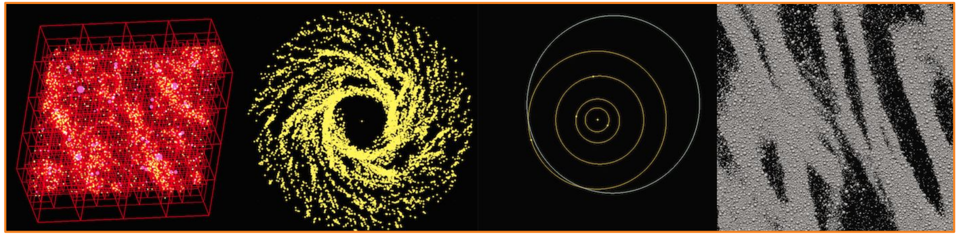
(Borovicka and Ceplecha, 1992)



# NUMERICAL INTEGRATION USING REBOUND

REBOUND is python package for N-body integrations, very flexible and can be customized to accurately and efficiently solve many problems in astrophysics.

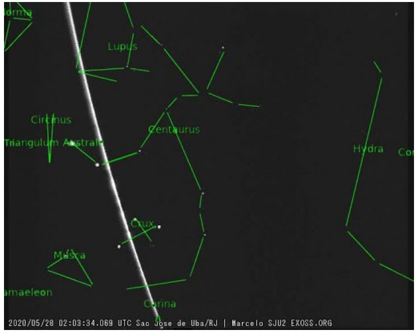
(Rein and Liu, 2012)

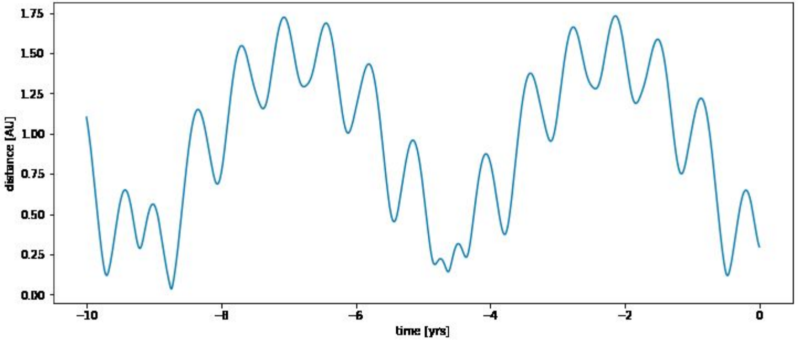


Example: Marcelo Mozer et al, 2020

using the IAS15 integrator

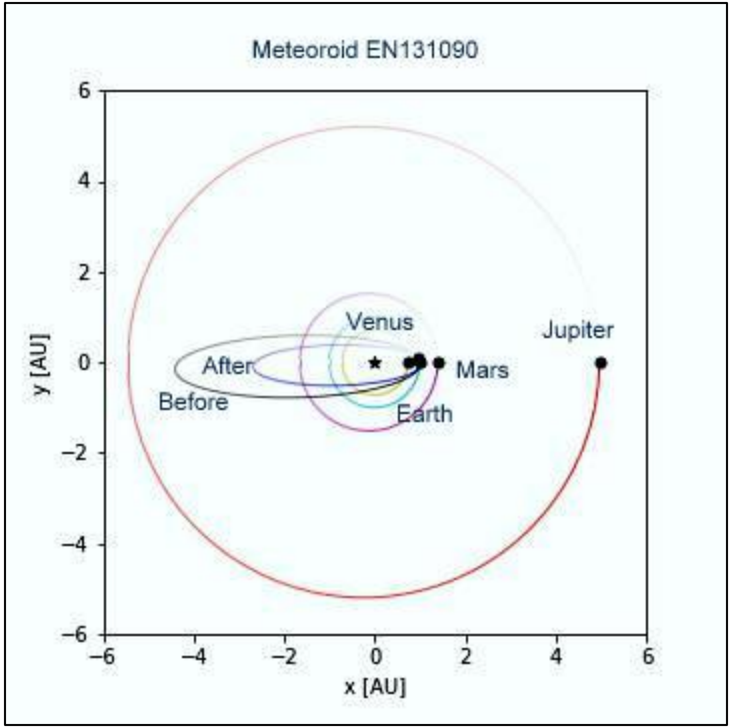
Aten type meteoroid



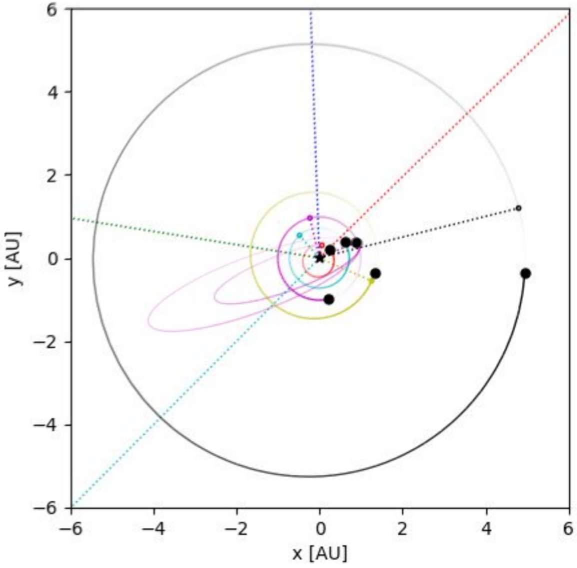
# NUMERICAL INTEGRATION: BEFORE/AFTER-ENCOUNTER

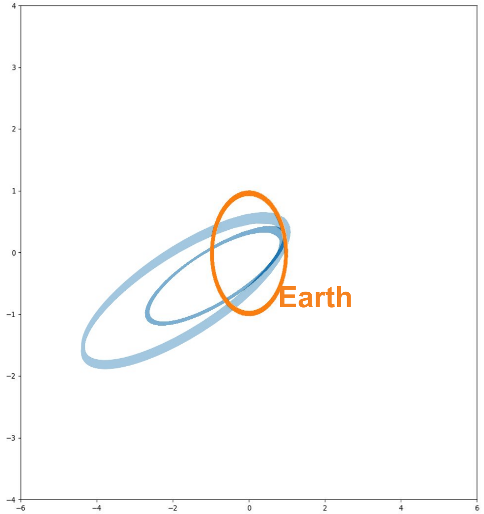
Rebound package



# NUMERICAL INTEGRATION: BEFORE/AFTER-ENCOUNTER

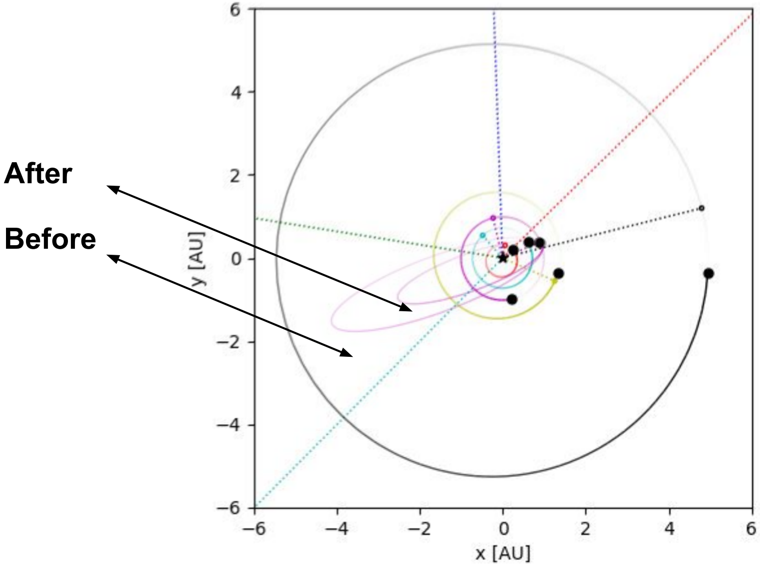
Rebound package

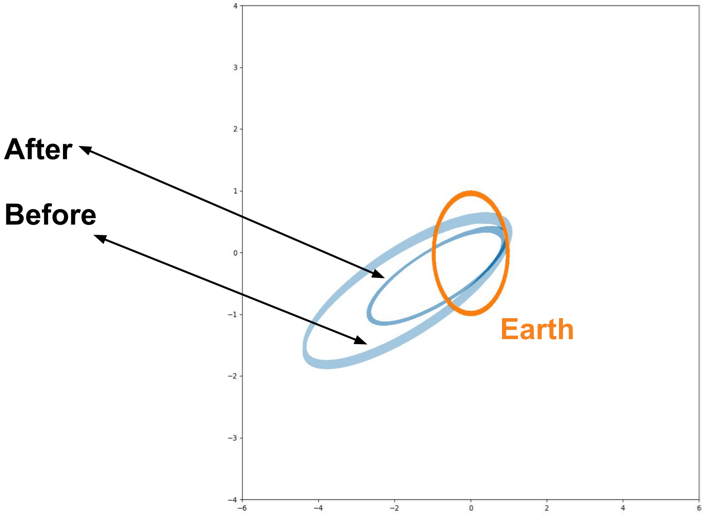


# NUMERICAL INTEGRATION: BEFORE/AFTER-ENCOUNTER

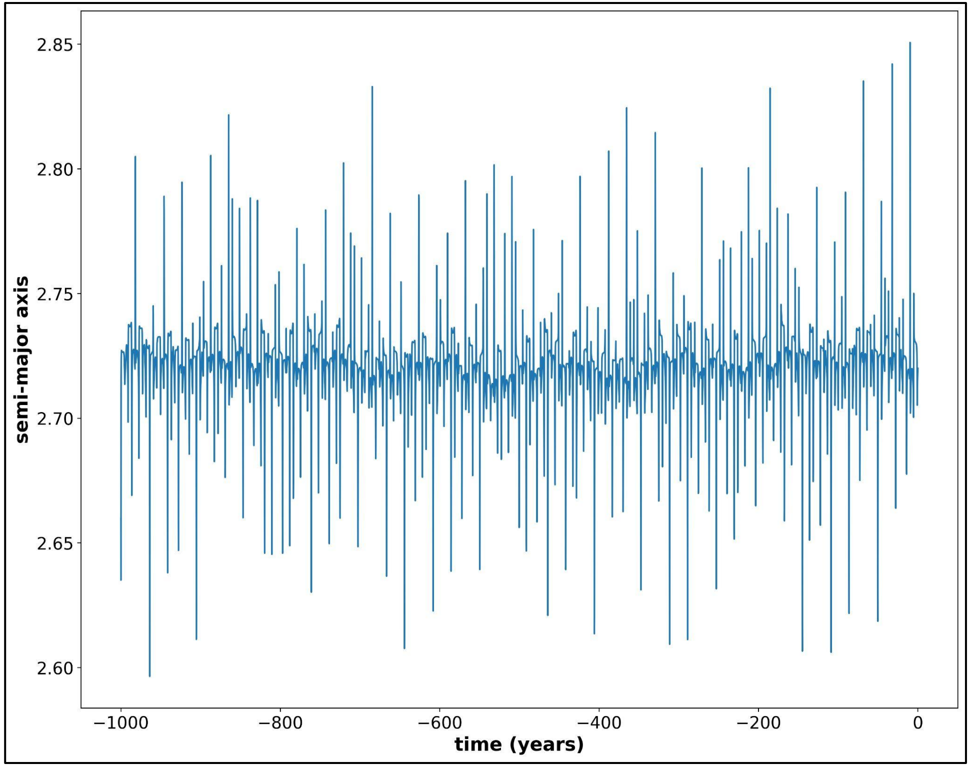
Rebound package

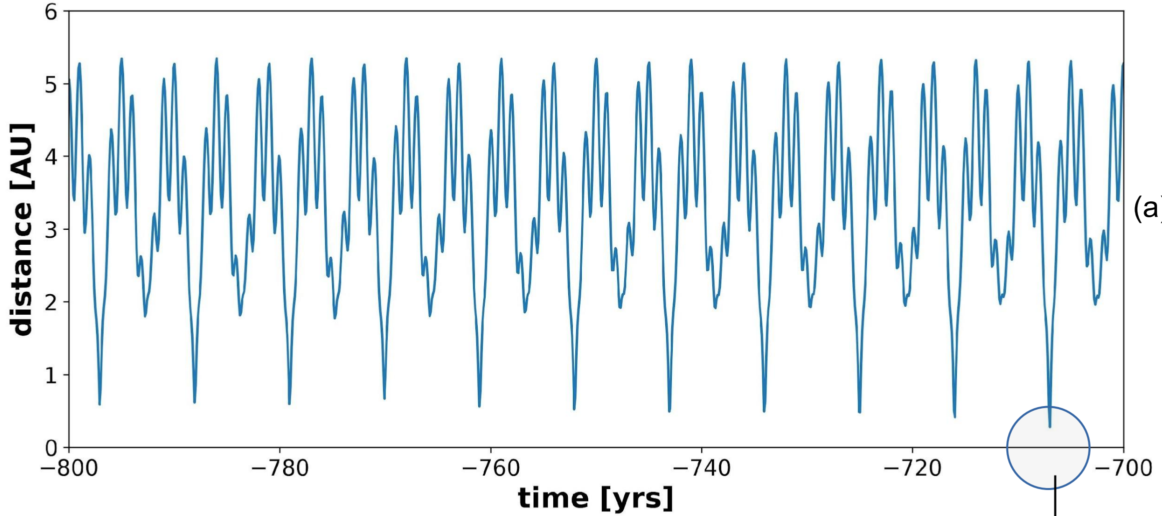


# NUMERICAL INTEGRATION: BEFORE-ENCOUNTER

## Rebound package



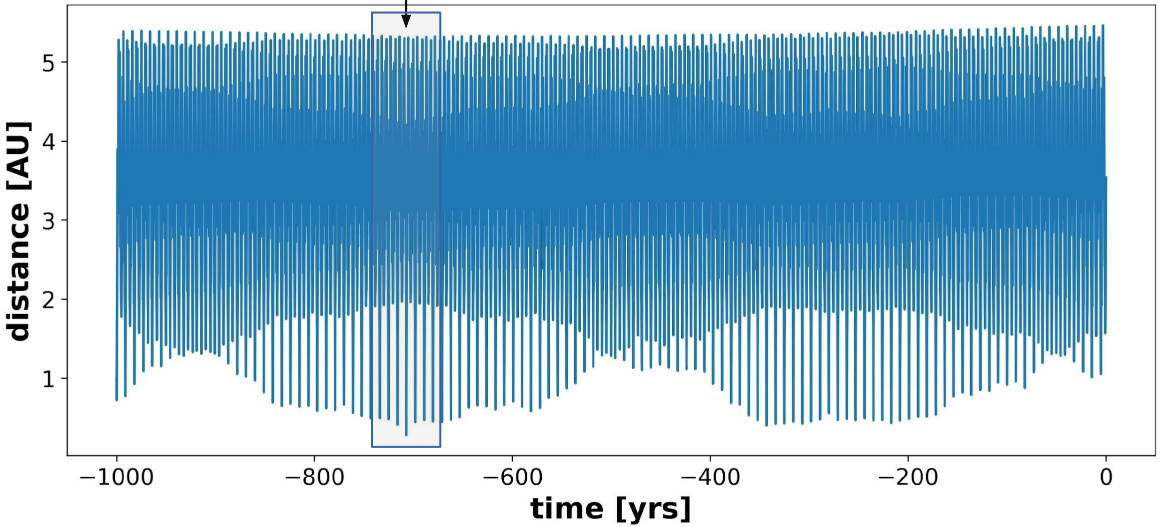



(a)

**Minimum distance (0.277549 AU )**
**occured at time:**

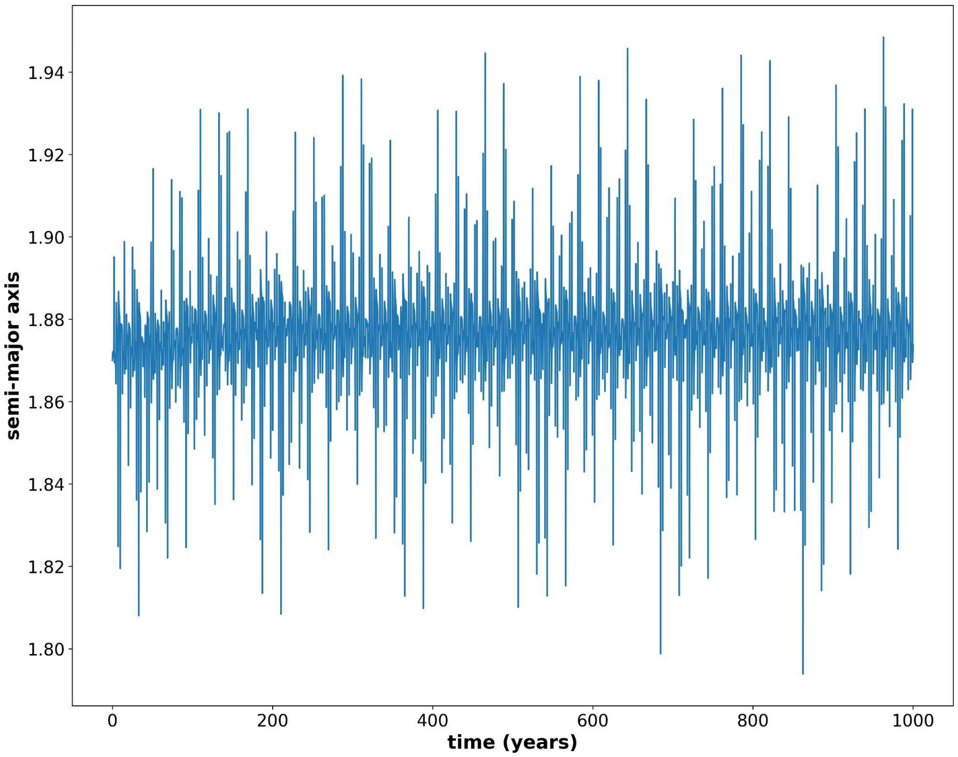
**$t_0$ - 706.97 years**

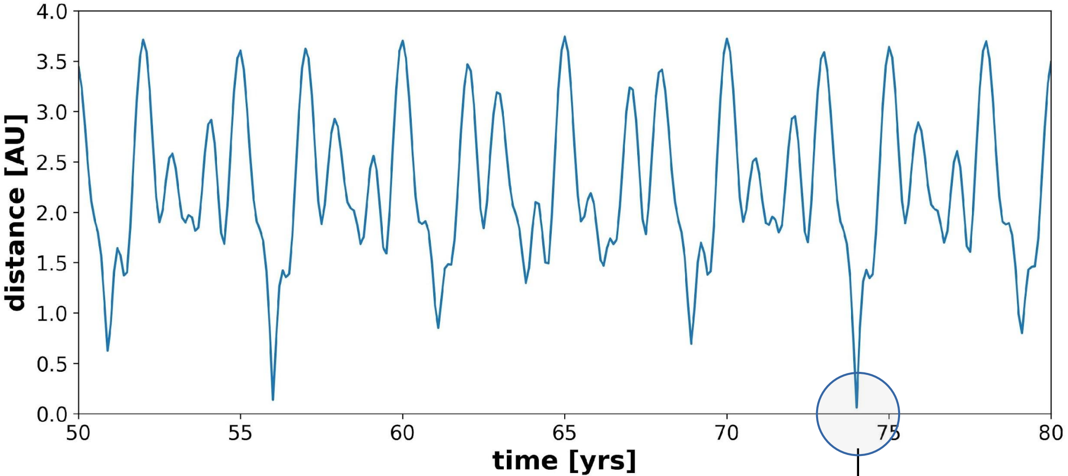
(b)



# NUMERICAL INTEGRATION: AFTER-ENCOUNTER

## Rebound package



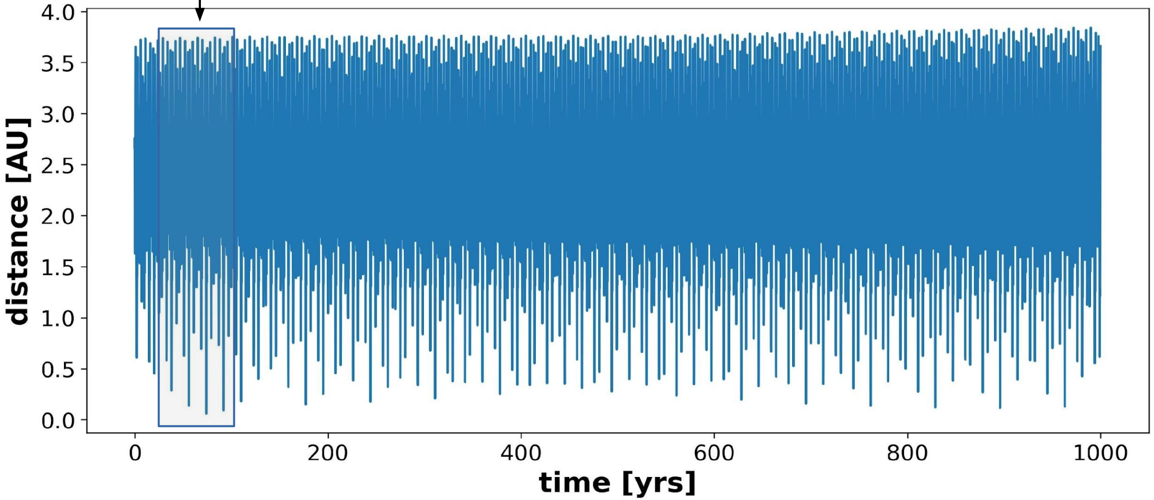



(c)

**Minimum distance (0.060304) occured at time :**

**$t_0$ + 74.007 years.**

(d)



# NUMERICAL INTEGRATION: SYMPLETIC 4th ORDER

**Numerical algorithms** : Because of the large separation of time-scales involved, from a day to billions of years, specialized integrators are needed to predict the orbital evolution of planetary systems over their entire lifetime that can correspond to up to $10^{12}$ orbits.

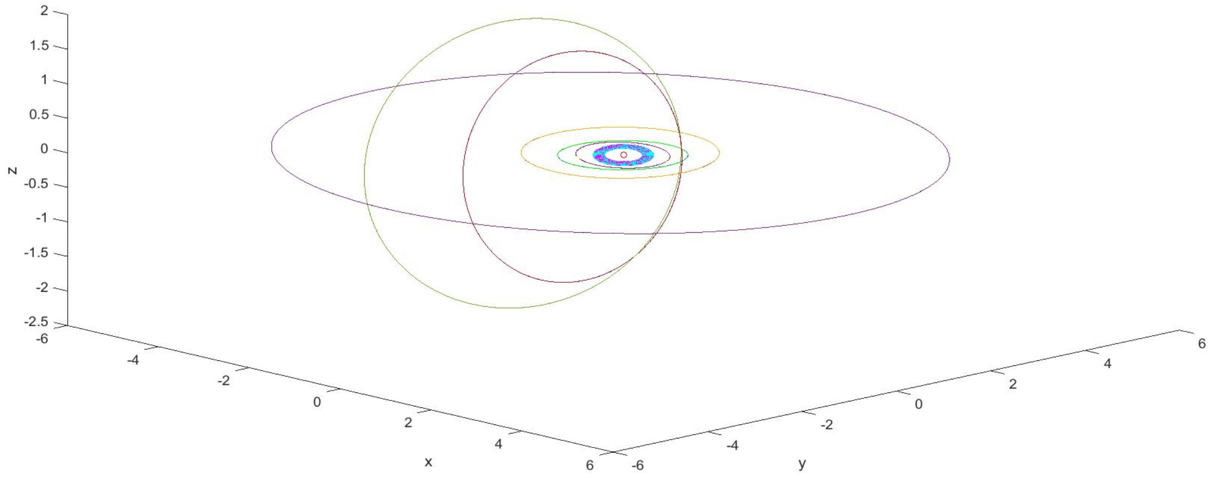
**Evolution of a dynamical system** , this is the case for many planetary systems including the Solar System. Higher order method that offers better accuracy at a fixed time-step.

**Wisdom–Holman integrator** → $H = A + \varepsilon B$ :

A→ interactions due to other planets, B → a perturbation .

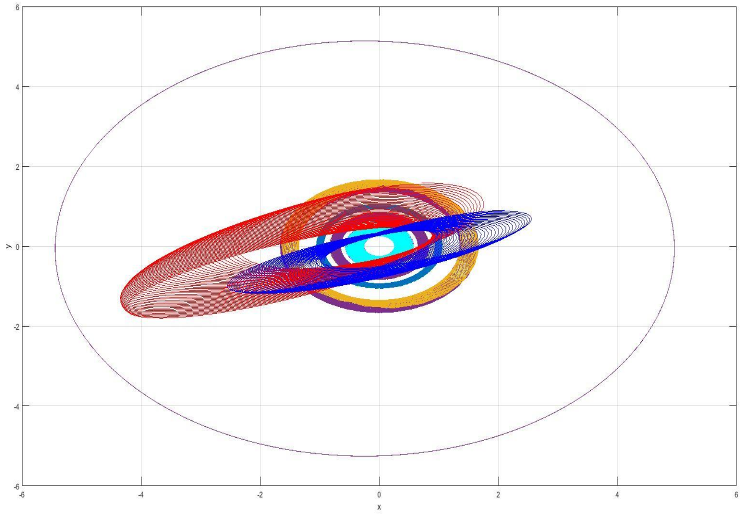
classical WH method

# NUMERICAL INTEGRATION: SYMPLETIC 4th ORDER

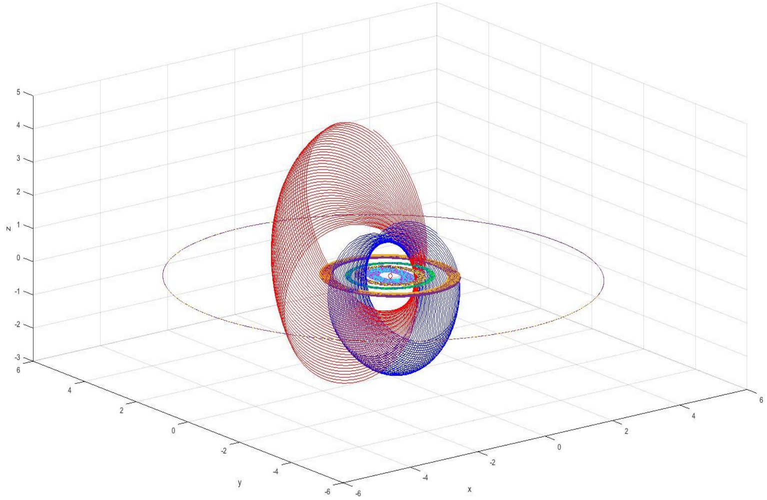


# NUMERICAL INTEGRATION: SYMPLETIC 4th ORDER

**upper view**




**side view**



# EARTHGRAZER: CONCLUSIONS

**Next steps:**

**- Improve velocity adjustments: More realistic model → trajectory is curved.**

**- Adapt the orbit calculation model (Brovicka & Ceplecha, 1992) for the case of grazers:**

better estimates: **a** , **e**

**- Apply the differential equation of dynamic initial mass.**