# EARTH-GRAZING FIREBALL'S RECURRENCE

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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 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.

## 1. INTRODUCTION

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.

In the context of this paper, the fundamental discussion can be described as

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an atmospheric fly-by of a small body (a grazer), that gravitational influence of the main body (Earth) changes the orbital evolution of the former in a way that future approximations could lead to an orbit that again crosses the planet path. Interesting topics of small bodies research arise from grazing close encounter studies, such as planetary impact risks predictions, frequency of meteoroid grazers and pre/post orbital modifications that potentially can be evaluated by symplectic integrations.

Thus, in order to study the dynamic properties of a close encounter by a meteoroid that grazes the Earth's atmosphere, we have chosen the October 13, 1990 fireball EN131090 event, registered by two Czech stations from the European Fireball Network (Borovicka and Ceplecha, 1992). Upon the available data, we run two distinct symplectic integrators: a non-separable fourth-order symplectic integrator (Neri, 1987; Szücs-Csillik, 2010; Anghel *et al.*, 2021) and the $15^{th}$-order modified Runge–Kutta integrator (IAS15) from REBOUND package (Rein and Spiegel, 2015), then discussing the results in this paper.

This work is divided into four sections: in the first section, we introduce the close encounter problem, showing its importance, the role involving risks - mostly from NEOs and the Earth-grazing closing approach; in the second section, we discuss more deeply close encounters problem from grazers perspective and the trajectory results of the EN131090 fireball, presenting the purposes of our investigations; in the third section we introduce the numerical modelling equations of motion analytically, for $n$-body in case of REBOUND software package and perturbed two-body, for Jupiter-Sun, Saturn-Sun, Earth-Sun, Mars-Sun, Mercury-Sun and Venus-Sun pairs simulations using the Neri's fourth-order symplectic integrator, analysing the results, comparisons and comments of the figures and graphics about before and after orbits in REBOUND and Symplectic simulations for a given period close approach and distance calculations. And finally, the fourth section is dedicated to discussing the results and conclusions.

### 1.1. CLOSE ENCOUNTERS PROBLEM

A theory interpreting mathematical close encounters mechanisms was developed by Opik (1976), it considers two bodies solution in two parts as a piece-wise two-body approach, it combines a hyperbolical solution during the fly-by for a new elliptical heliocentric orbit. Later improvements introduced by Milani *et al.* (2000) and Valsecchi *et al.* (2003) supersede theoretical limitations related to orbits with Minimum Orbital Intersection Distance (MOID) very close to zero and the basic theory does not consider dependence of the subsequent encounters with the previous ones, thus innovating with the concept of resonant returns and keyhole mechanisms*.

*Small regions of an impact plane of a specific close encounter that if an object pass through one of them, it will hit the Earth in a subsequent return.

Two dynamic aspects have to be considered about close encounters: the sphere of influence (SOI) and MOID, as according to mutual distances temporal gravitational forces of Earth can superpass the Sun's attraction (Solar System Central Body) and the distance between the body and the planet orbit become so close that could indicate a future collision (Tommei, 2021). Those encounters have the capacity to change orbits in a way that possible subsequent encounters could not be independent of the occurrence of the previous one (resonant return).

At the early stages of our planetary system, close encounters of Giant ice planets with protoplanetary bodies and planetary migrations resonances defined some small body disk structures (Nesvorný, 2018). Many studies and numerical modelling of the initial formation and evolution of the Solar System demonstrate the protoplanetary close approaches were one of the fundamental mechanisms for the current structure of Main Belt Asteroids, Trojans and Kuiper objects, these reservoirs are responsible for near-Earth objects (NEOs) replenishing and periodic comets, respectively. Also, dynamic mechanisms involving close encounters are crucial for understanding of terrestrial planets resurfacing by intense cratering of Mercury, Venus, Moon, Earth and Mars, during Late Heavy Bombardment (Bottke and Norman, 2017).

Minor bodies as asteroids, comets and meteoroids (parts of comets/asteroids $\leqslant$ 1 m) are subject to close encounters with considerable more massive bodies (*i.e.* the planets). Investigating this mechanism is fundamental for understanding the current orbital evolution of objects such as NEOs, Jupiter family comets (JFCs), long period and hyperbolic comets that can reach out or cross Earth orbit.

### 1.2. EARTH IMPACTS

Our planet has experienced in recent times many considerable impacts as the Tunguska event in 1908 that devastated 80 million trees around an area of 2150 km$^2$, in the Siberian region (Boslough, 2015). This event was supposed to be caused by a small body of 40 m that disintegrated completely in the air. In 2007, the Carrancas impact created a crater of 13.5 m and a depth of 5 m, the estimated size body is "only" 2 m (Moreno-Ibanez, 2018), and the most recent case of Chelyabinsk superbolide in 2013. The latter, was caused by an asteroid with an approximate size of 20 m that crashed in the atmosphere and an air blast injured more than thousand people, causing millions of euros in damages.

Such events might take place every 50 years, so efforts have been done to develop new tools for the detection of planetary-small bodies encounters that might cause potential impacts, in a way that can be estimated and its probability calculated. In Figure 1 we show a plot of cumulative impact risks (Boslough *et al.*, 2015) by energy, NEA population, probabilities, sizes and absolute magnitude $H$, where the estimates of impact frequencies use a straight-line power-law population and many catastrophic events are marked (Perna *et al.*, 2013).

Thus, early detection, accurate estimations and propagation of their states with associated uncertainties set (Chesley *et al.*, 2002) and further follow-up of NEOs and bodies of tens of meters in size are crucial. But many small bodies are still difficult to detect due to distances, proximity to the Sun glare, low albedo and higher absolute magnitude that could hit Earth without any previous warning.

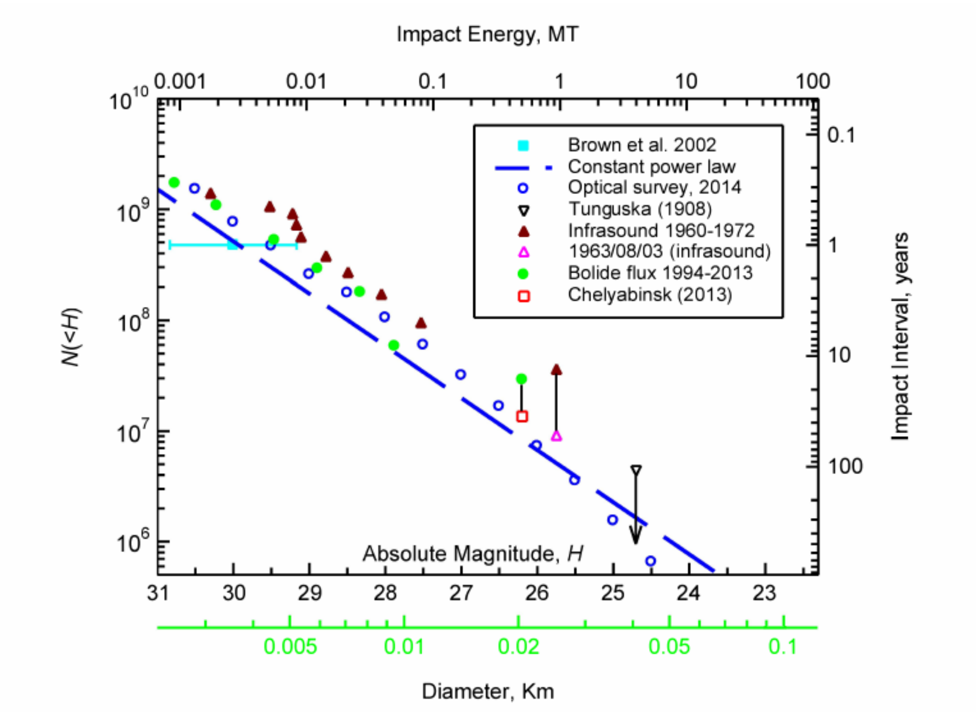


Fig. 1 – Estimated cumulative population of small NEAS The bottom scale shows the size of the objects. The left scale shows how many are that size or larger, the top scale is the energy that would be released on impact, the right scale shows the frequency with which impacts might occur.

Furthermore, NEAs $\geqslant 140$ m with MOID $\leqslant 0.05$ pose a serious threat, and they are massive enough to survive atmosphere penetration and cause local or regional scale destruction. These are known as PHAs (Potentially Hazardous Asteroids) and a catastrophic impact of such magnitude is expected to occur once every million years. An emblematic example is PHA (99942) APOPHIS, discovered in December 2004 with a possible impact of Torino scale 2 in 2009, however further observations excluded a collision.

### 1.3. EARTH-GRAZING CLOSE ENCOUNTERS

While many studies show that small kilometer to meter-size objects occasionally experience close encounters with Earth and other planets such as Mars, Venus and Jupiter, very few efforts have been made to study grazing bolides or superbolides (only 10 grazing fireballs were registered in current scientific literature). They survive atmosphere passage and return to interplanetary space, with orbital parameters changed, sending material from one part of the inner Solar System to another (Shober *et al.*, 2020). Thus, it is extremely important to understand the encounter mechanisms as it can improve our estimation of object size-flux frequency.

As meteor network monitoring systems have been expanding worldwide, an ever increasing precision in trajectory computations is allowing better constraints of dynamical and physical properties characterization, mainly when large events such as superbolides and Earth-grazings are registered. So, many citizen science projects such as MOROI, FRIPON, EXOSS and networks elsewhere (for more details see Anghel *et al.*, 2019; Colas *et al.*, 2020; De Cicco *et al.*, 2018) are playing a fundamental role in identification and orbit evaluation of potential grazing fireballs events.

## 2. THE EARTH-GRAZING FIREBALL PROBLEM

Meteoroids Meteroids originate from cometary debris or dust and grains from fractured NEOs, and depending on their brightness levels during the atmospheric penetration they can be: meteors, bolides (absolute magnitude $\leqslant -4$) or superbolides (absolute magnitude $\leqslant -12$). Tiny meteoroids (below 0.01 m) and ones with low bulk density at height velocities, above hypersonic limits during air penetration are completely destroyed. Occasionally, parts of a hard material of meteoroids with centimeter to meter sizes can survive the ablation and leave meteorites or even return to space as grazing fireballs.

If a meteoroid has a trajectory through the Earth's atmosphere at a low-angle, almost tangentially, in a way that part of its own material survives ablation phenomena and returns to interplanetary environment we have a typical grazing fireball (bolide or superbolide type). The Figure 2 displays a graphic scheme for the geometry of a close encounter passage.

Many grazing fireballs have been registered, thanks to growing amateur citizen science projects dedicated to meteors video registering (Anghel *et al.*, 2021). However, the first scientific observation dates back to the seventies, when a daylight bolide crossed United States and Canada skies, on August 10, 1972, which trajectory was 1500 km long (usual luminous meteor track $\leqslant$ 100 km), with an estimated initial mass of $10^5$ to $10^6$ kg (Ceplecha, 1979).

The grazing fireball phenomena have been reported for a long time, e.g. in

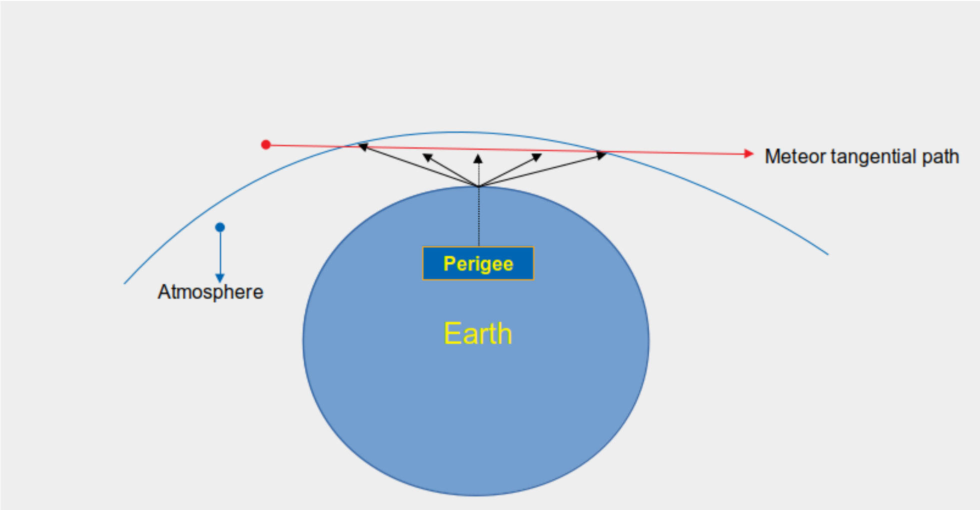


Fig. 2 – A grazing meteoroid enter tangentially in the Earth's atmosphere and return to space.

1784 "The Great Meteor" was observed, moving in a path more than 160 km, in 1860 another grazing was observed (Olson *et al.*, 2010), last century the "Great Meteor procession" crossed North and South America continents (Chant, 1913; Denning, 1916). Shober *et al.* (2020) made a summary of Earth-grazings scientifically observed that we updated and reproduce at the following list:

- On August 10, 1972, a daylight Earth-grazing fireball crossed the United States and Canada, registered photographically (Ceplecha, 1979).
- On October 13, 1990, grazing fireball crossing East Europe (Borovicka and Ceplecha, 1992).
- On October 1992, Meteorite Peekskill, over the eastern United States (Ceplecha *et al.*, 1996).
- On 2003, Ukraine grazing meteor (Kozak and Watanabe, 2017).
- On March 29, 2006, a grazing over Japan (Abe *et al.*, 2006).
- On August 27, 2007, the grazing was observed by the European Fireball Network (Spurný *et al.*, 2008).
- On June 10, 2012, the first grazing associated with a meteor shower in the scientific literature, daytime ρ - *Perseids* shower (Madiedo *et al.*, 2016).
- On March 31, 2013, a grazing meteor over Germany and Austria (Oberst *et al.*, 2014).

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

The Earth-grazings have a luminous path of hundred to thousands of kilometers moving tangentially through the atmosphere, however, their analyses with the standard assumptions of meteor trajectory ($\approx$ 100 km) could bring unrealistic dynamic effects. So, a special method was proposed by Borovicka and Ceplecha (1992) that can be applied to long grazing meteors such as the October 13, 1990 fireball that after an observed trajectory ($>$ 400 km) it returned to interplanetary space.

### 2.1. THE EN131090 OCTOBER 13, 1990 EARTH-GRAZING FIREBALL

The second Earth-grazing fireball scientifically registered (Borovicka and Ceplecha, 1992) occurred on October 13, 1990. It was observed by three independent observers in Czechoslovakia, a radio reflection obtained in Denmark and a photographic report done by two European Fireball Network stations (denoted as bolide EN131090). An all-sky photo of the luminous track during flight is presented in Fig. 3.

This grazing meteoroid had an estimated initial mass of 44 kg, losing only $0.35$ kg, with a maximum brightness of $-6.45$ absolute magnitude and an almost constant velocity of $41.74 \pm 0.24$ km $\cdot$ s$^{-1}$, during all luminous paths it travelled about 409 km. The remaining material went out into interplanetary space with solidified fusion crust on its surface.

We developed a python code from FORTRAN program of Olson *et al.* (1991) that simulate the Earth-grazing meteoroids, during the atmospheric flight, it can predict the bolide trajectory as it goes down, reaches perigee and returns to the interplanetary environment, including gravitational attraction that bends long-duration moving on nearly-tangential paths. It was used to simulate the October 13, 1990 Earth-grazing fireball EN131090 and the outputs: relative time, ground track, height, speed, deceleration, mass loss and visual magnitude are in good accordance with the observations.

Borovicka and Ceplecha (1992) fitted 88 time marks observations of the meteoroid EN131090 inside a time interval of 6.9 seconds, hence it was possible to make precise calculations of absolute magnitude, velocities and decelerations. Since the brightness only varied from a minimum of M: -5.96 to a maximum of M: -6.45 during the perigee approach, the velocity, V: 41.74 $\pm$ 0.24 km $\cdot$ s$^{-1}$, is considered constant, and with the air drag deceleration determined at perigee point, the authors

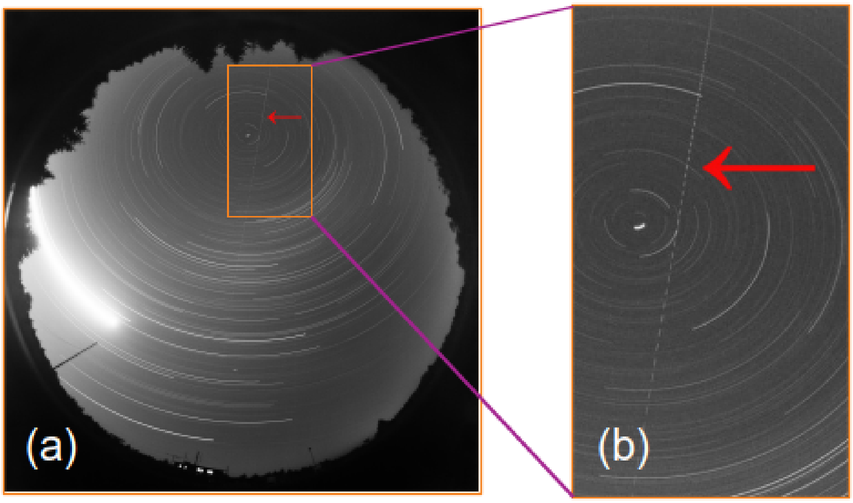


Fig. 3 – Figures: (a) An All-sky picture using a fish-eye objective Zeiss Distagon 3.5/30 mm of the grazing bolide EN131090 that flew above Czechoslovakia and Poland on October 13, 1990, and captured by the hydro-meteorological station at Červená hora, situated that time at Czechoslovakia, originally taken from a glass photographic plate. (b) The zoomed image shows the interrupted trackings by a shutter at 12.5 rps, pointed by a pos-inserted red arrow. Credits: European Fireball Network - RNDr. Pavel Spurný, CSc, Astronomický ústav AVČR.

conclude that the fireball is likely an ordinary chondrite, with an initial mass of 44 kg and a mass loss of 0.35 kg.

Using the parameters discussed above related to velocity, mass and meteoroid's most probable composition, we run the code generating outputs that describe in good agreement the brightness, heights and mass loss. Figure 4 displays two plots with physical characterization, showing that the observed luminous path of the grazer losses almost 0.2 % of its mass, reaching an absolute magnitude around -6.40, during the perigee approach at height $\approx$ 100 km.

### 2.2. A SYMPLECTIC INTEGRATOR SCHEME FOR CLOSE ENCOUNTERS STUDIES

To investigate the astrodynamic characteristics of a grazer, we need to implement a numerical integration of backward and forward time that can predict the orbital parameters before/after the closest approach, in order to help to answer two main questions that emerged from this topic:

1. If a meteoroid becomes an Earth-grazing fireball (and it grazes the Earth's atmosphere), it comes back, escapes or collide with Earth in time? (The answer

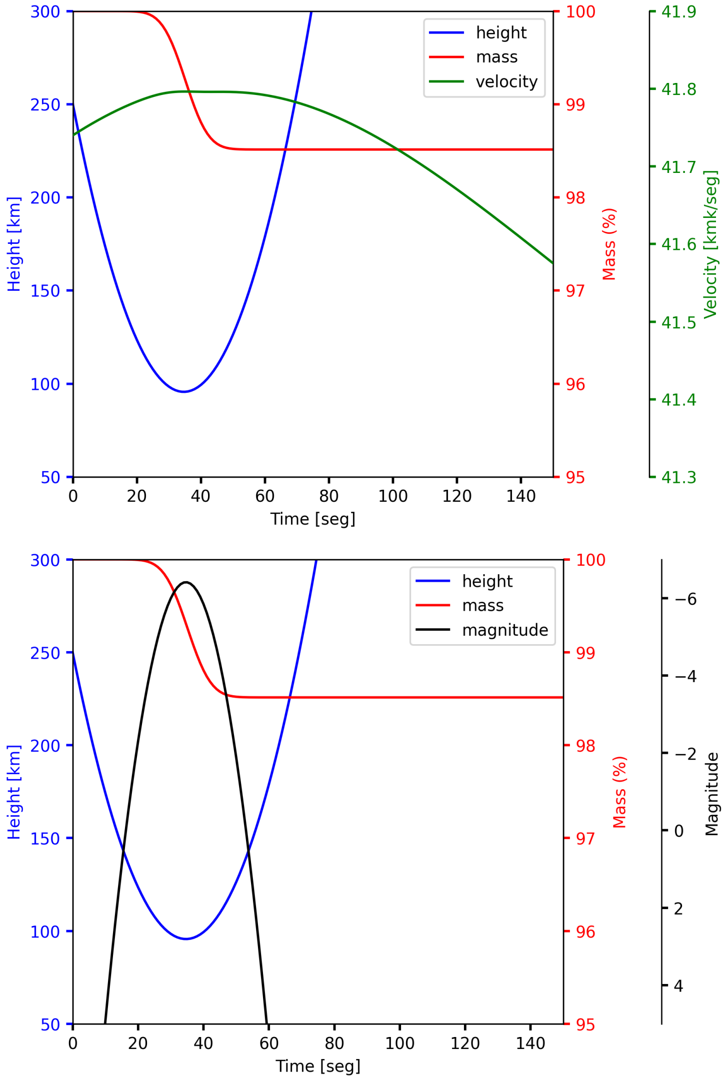


Fig. 4 – During the atmospheric path, the meteoroid EN31090 loose ≈ 0.35 kg of mass, during the 409 km of observed luminous path, then returning to space. The simulation results show in the upper plot an almost near constant velocity (green curve) with an abrupt slope (in red color) of mass around perigee point, in its descend journey (blue color). In the bottom plot the absolute magnitude (black curve) as the bolide is ablated.

depends on the meteoroid's orbit after the Earth-grazing moment).

2. Analysing the meteoroid's orbit before the Earth-grazing moment, could we say if it had close encounters in the past?

Some integrators are better suited to simulate close encounters than others, for example, the non-symplectic integrator IAS15 has an adaptive timestep scheme that resolves close encounters very well (Rein and Spiegel, 2015). Whereas integrators that use a fixed time-step like WHFast are more likely to miss close encounters (Rein and Tamayo, 2015). During the close approaches to the Earth, the meteoroid's orbit is continuously perturbed by the planet's gravity.

At the same time, a core problem arises particularly for orbit integrations, as we observe the "hop-phenomenon" (Szenkovits *et al.*, 2002; Csillik, 2003) during a close encounter at time interval $t_1 - t_2$ when at the moment $t_1$, we notice the meteoroid's orbital parameters before the perturbation effect of the Earth and at the moment $t_2$, we observe the meteoroid's orbital parameters after the close encounter with Earth.

So, two numerical integrators to simulate the long term gravitational dynamics of a meteoroid were tested and analyzed: a non-separable fourth-order symplectic integrator (Neri, 1987; Szücs-Csillik, 2010; Anghel *et al.*, 2021; De Cicco and Szücs-Csillik, 2022) (Neri integrator) and the implicit integrator with adaptive time stepping, $15^{th}$-order modified Runge–Kutta integrator (IAS15), incorporated in the package REBOUND (Rein and Spiegel, 2015). As it is generally known, the numerical integration methods which inherit the symplecticity of a differential equations tend to better approximate the trajectory of a symplectic differential equation.

Moreover, the fourth-order symplectic integrator scheme is time reversible because it is symmetric. It is common knowledge that time reversibility is important, it ensures the two first integrals, *i.e.* the conservation of energy and area preserving.

Therefore, in order to answer the two main questions purposed, facing the "hop-phenomenon" a study of the case of the EN131090 grazer was chosen because it has very precise trajectory values defined. Its orbital elements from Borovicka and Ceplecha (1992) listed in Table 1 show that during the approach with the Earth the semi-major axis decrease from 2.72 ± 0.08 to 1.87 ± 0.03 AU, causing a considerable reduction of the period and eccentricity (Clark and Wiegert, 2011). Thus, it is suitable to test the symplectic integrators mentioned above, applying before initial conditions (IC) for the retrograde integration and the after IC for prograde integration, analysing possible close encounters and collision studies.

### 2.3. THE METEOROID'S ORBIT BEFORE AND AFTER CLOSE ENCOUNTER WITH EARTH

Let us take a coordinate system $x$, $y$, $z$ with its origin at Earth's center. We are considering perturbations due to the oblateness of Earth, the atmospheric drag and the lunisolar attraction. The differential equations of meteoroid motion in rectangular coordinates have the form:

$$\frac{d^2x}{dt^2} = \frac{\partial U}{\partial x},$$

*Table 1*

Elements of the EN131090 meteoroid before and after from Borovicka and Ceplecha (1992) updated for J2000.0

| Heliocentric orbits parameters (J.2000.0) | | |
|---|---|---|
| | before | after |
| $\alpha_G$ | $97^\circ.67 \pm 0^\circ.01$ | $97^\circ.28 \pm 0^\circ.01$ |
| $\delta_G$ | $-40^\circ.58 \pm 0^\circ.01$ | $-36^\circ.34 \pm 0^\circ.01$ |
| $v_G$ | $40.22 \pm 0.17$km/s | $40.22 \pm 0.17$km/s |
| $a$ | $2.72 \pm 0.08$AU | $1.87 \pm 0.03$ AU |
| $P$ | $4.5 \pm 0.2$yr | $2.56 \pm 0.06$yr |
| $e$ | $0.64 \pm 0.01$ | $0.473 \pm 0.009$ |
| $q$ | $0.9923 \pm 0.0001$ AU | $0.9844 \pm 0.0002$ AU |
| $Q$ | $4.45 \pm 0.15$ AU | $2.76 \pm 0.07$AU |
| $\omega$ | $9^\circ.60 \pm 0^\circ.01$ | $16^\circ.60 \pm 0^\circ.02$ |
| $\Omega$ | $18^\circ.973$ | $19^\circ.672$ |
| $i$ | $71^\circ.39 \pm 0^\circ.02$ | $74^\circ.40 \pm 0^\circ.02$ |

$$\begin{aligned} \frac{d^2y}{dt^2} &= \frac{\partial U}{\partial y}, \\ \frac{d^2z}{dt^2} &= \frac{\partial U}{\partial z}, \end{aligned} \qquad (1)$$

where,

$$U = U_{00} + U_{20} + U_{22} + U_{30} + U_{31} + U_{32} + U_{33} + U_{40} + U_{50} + U_A + U_{RP} + U_{LS}, \qquad (2)$$

and the particular terms are respectively

$$\begin{aligned}
U_{00} &= \frac{\mu}{r}, \qquad (3)\\
U_{20} &= \frac{1}{2}\mu R^2 c_{20} \cdot \left(\frac{3z^2}{r^5} - \frac{1}{r^3}\right), \\
U_{22} &= 3\mu R^2 \left[\left(\frac{x^2-y^2}{r^5}c_{22} + \frac{2xy}{r^5}s_{22}\right)\cos 2s + \right. \\
&+ \left.\left(\frac{2xy}{r^5}c_{22} - \frac{x^2-y^2}{r^5}s_{22}\right)\sin 2s\right] \\
U_{30} &= \frac{1}{2}\mu R^3 c_{30} \cdot \left(\frac{5z^3}{r^7} - \frac{2z}{r^5}\right), \\
U_{31} &= \frac{3}{2}\mu R^3 \left[\left(\left(\frac{5xz^2}{r^7} - \frac{x}{r^5}\right)c_{31} + \left(\frac{5yz^2}{r^7} - \frac{y}{r^5}\right)s_{31}\right)\cos s + \right. \\
&+ \left.\left(\left(\frac{5yz^2}{r^7} - \frac{y}{r^5}\right)c_{31} - \left(\frac{5xz^2}{r^7} - \frac{x}{r^5}\right)s_{31}\right)\sin s\right],
\end{aligned}$$

$$
\begin{aligned}
U_{32} &= 15\mu R^3\left[\left(\left(\frac{(x^2-y^2)\cdot z}{r^7}\right)c_{32}+\left(\frac{2xyz}{r^7}\right)s_{32}\right)\cos 2s+\right.\\
&+\left.\left(\left(\frac{2xyz}{r^7}\right)c_{32}-\left(\frac{(x^2-y^2)\cdot z}{r^7}\right)s_{32}\right)\sin 2s\right],\\
U_{33} &= 15\mu R^3\left[\left(\left(\frac{x\cdot(x^2-3y^2)\cdot z}{r^7}\right)c_{33}+\left(\frac{y\cdot(3x^2-y^2)}{r^7}\right)s_{33}\right)\cos 3s+\right.\\
&+\left.\left(\left(\frac{y\cdot(3x^2-y^2)}{r^7}\right)c_{33}-\left(\frac{x(x^2-3y^2)\cdot z}{r^7}\right)s_{33}\right)\sin 3s\right],\\
U_{40} &= \frac{1}{8}\mu R^4 c_{40}\cdot\left(\frac{35z^4}{r^9}-\frac{30z^2}{r^7}+\frac{3}{r^5}\right),\\
U_{50} &= \frac{1}{8}\mu R^5 c_{50}\cdot\left(\frac{63z^5}{r^{11}}-\frac{70z^3}{r^9}+\frac{15z}{r^7}\right),\\
U_A &= -\frac{1}{2}\frac{\rho C_D A}{m}v_r\overline{v_r},\\
U_{RP} &= p\cdot\frac{A}{m},\\
U_{LS} &= \frac{\mu'}{r'}\cdot\left(1+\frac{r^2}{2r'^2}\cdot(3\cos(2\psi-1))\right)+\frac{\mu''}{r''}\cdot\left(1+\frac{r^2}{2r''^2}\cdot(3\cos(2\psi-1))\right),
\end{aligned}
$$

where $\mu$ is the gravity constant for the Solar System (in our case $\mu = 39.4732$ $AU^3/year^2$), $r$ is the distance from the center of mass to the meteoroid, $R$ is the equatorial radius of the Earth ($R = 0.000042$ $AU$), $c_{20} = -1082.4$, $c_{22} = 0.75$, $s_{22} = -0.61$, $c_{30} = 2.57$, $c_{31} = 0.87$, $s_{31} = -0.27$, $c_{32} = 0.08$, $s_{32} = -0.09$, $c_{33} = -0.07$, $s_{33} = 0.129$, $c_{40} = 2.01$, $c_{50} = 0.07$ are zonal and tesseral coefficients, $s$ is the argument of latitude, and $\rho$ is the atmospheric density, $C_D$ is the drag coefficient, $A/m$ is the cross-section to the mass of meteoroid ratio, $v_r$ is the meteoroid velocity vector relative to atmosphere, and $p$ is the solar light pressure at the distance of one AU, $\mu', \mu''$ are the masses of the disturbing bodies (Moon, Sun) multiplied by the gravitational constant, $r', r''$ are the radius vectors of the disturbing bodies, $\psi$ is the Sun-Moon distance angle as seen from the Earth.

Let us consider the simple exponential atmospheric model

$$\rho = \rho_p \exp\left(\frac{r_p - r}{H}\right), \tag{4}$$

where $\rho_p$ is the density at the initial perigee point, obtained via the NRLMSISE-00 model (Picone *et al.*, 2002), $r_p$ is the initial distance of the meteoroid from Earth's surface and $H$ is the scale height. Let us denote $B = \frac{m}{C_D A}$ the Ballistic coefficient, and we assume that the atmosphere rotates at the same angular speed as the Earth.

Then, the relative velocity vector is

$$\mathbf{v_r} = \mathbf{v} - \omega \times \mathbf{r}, \tag{5}$$

where $\omega$ is the initial rotation vector of the Earth around the $z$ axis with $\omega_e = 7.29 \cdot 10^{-5}$ rad $\cdot$ s$^{-1}$. The relative velocity vector is $\mathbf{v_r} = (v_x + \omega_e y, v_y - \omega_e x, v_z)$.

### 3. NUMERICAL INVESTIGATION: RESULTS

An Apollo-type orbit of the meteoroid EN121090 was obtained (see Figures 5 and 6) based on the integration of differential equations of motion (3) using the high accuracy non-symplectic integrator with adaptive time-stepping (IAS15) and the Neri's symplectic 4th order integrator (Rein and Spiegel, 2015; Csillik, 2004).

The semi-major axis is used to compute the total energy of the orbit and together with eccentricity allows us to compute the angular momentum (see Table 1). The meteoroid's angular position in the orbit at a given epoch is defined by the true anomaly. For that reason, the semi-major axis, the eccentricity, and the true anomaly give information about the size and shape of the meteoroid's orbit, and its location in the orbital plane (Roy, 1988; Seidelmann, 1992; Vallado, 2013). This close approach of EN131090 meteoroid to the Earth changed its orbital elements in such a way that possible future encounters could not be independent of the occurrence of the previous one, given the concept of resonant returns explained in the subsection 1.1.

As shown in Figure 5, the meteoroid's inclination angle is almost perpendicular to the ecliptic. We marked its trajectory before the close approach to the Earth with blue colour, which shows it dancing around the Earth in an elliptical orbit. According to the authors, this dancing around Earth's orbit would have led to a close approach sooner or later. The trajectory marked in red is the orbit after a close encounter with Earth. It is noticeable how much the proximity of the Earth affected the EN131090 meteoroid's orbit as if it was thrown out. Between the Mars-Jupiter region, the meteoroid's aphelion moved closer to Jupiter's orbit, but its perihelion remained close to Earth.

Based on our numerical integration, this means that its 2.5-years return is worth tracking. Due to the precessional movement of the meteoroid's orbit, its perihelion slowly moves away from the Earth's orbit for our 1000-year simulation period (see Figure 5) The meteoroid's orbit is slowly shifting in the direction of the orbit of Mars. If it gets closer to Mars, the meteoroid's orbit may be affected by the planet, changing its orbital elements.

Using the same data available in Table 1, we run the IAS15 integrator of the REBOUND package, repeating the same 1000 years back/forward integrations for close encounters to Mars, Venus, Mercury and Jupiter, to try to find out minima approaches that could affect the orbital shape of the meteoroid.

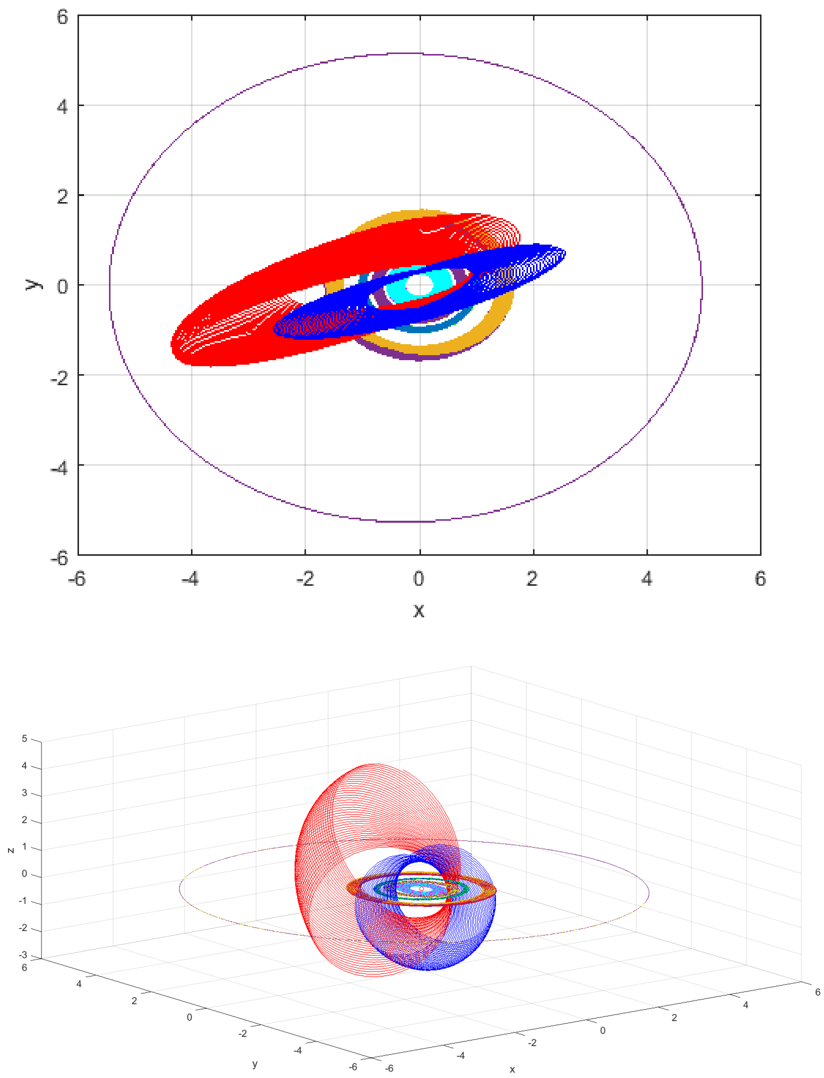


Fig. 5 – The EN131090 meteoroid orbit - before and after - using Neri 4th order integrator, and its relative position to the orbits of Mercury, Venus, Earth, Mars and Jupiter.

In Figure 7 the two plots of semi-major axis present variations for 1 000 years, backward and forward in time, using initial conditions of pre and post encounter described in Table 1. The variations are more than 10% which show that the meteoroid orbit is influenced by Earth (and less degree by Mars) enough to be pertubed.

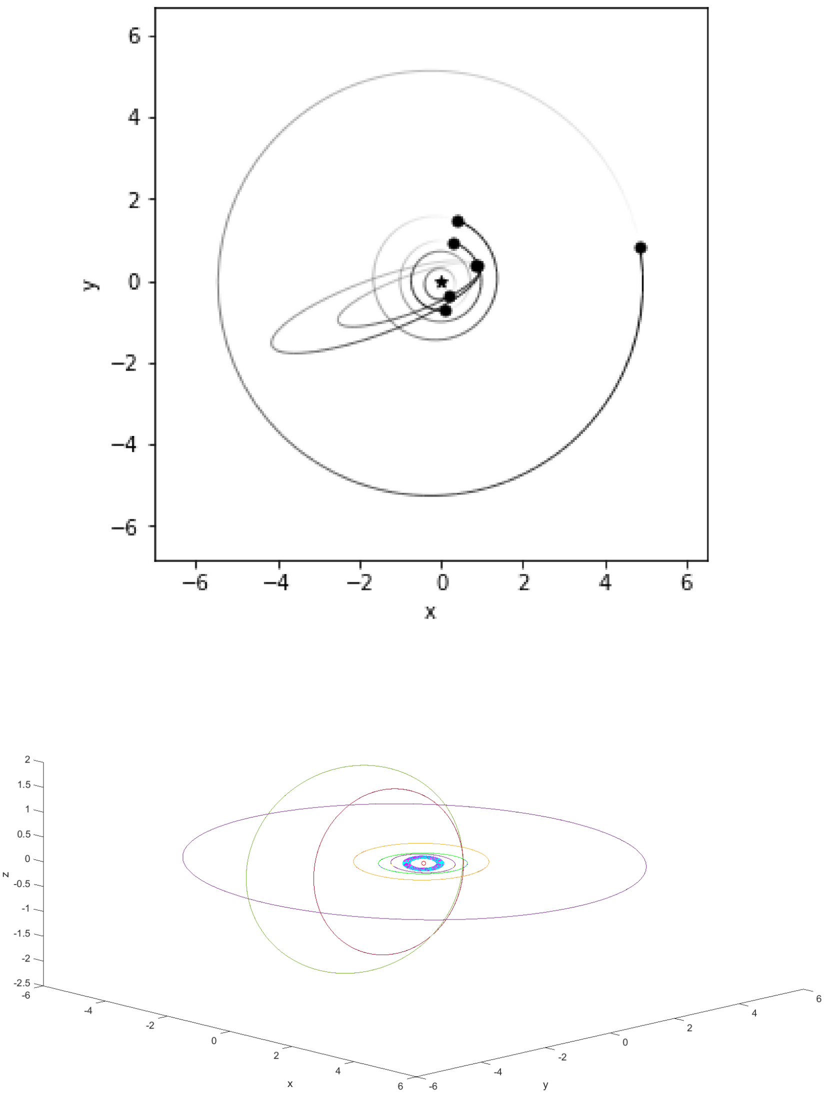


Fig. 6 – The EN131090 meteoroid orbit (projected to the ecliptic plane) before and after orbits using Rebound $n$-body integrator, and its relative position to the orbits of Mercury, Venus, Earth, Mars and Jupiter.

The simulations showed that among the planets mentioned above, the object had a close approach only with the Earth. Backward integration found only an encounter 706.97 years back, at 0.277549 AU distance and the forward integration got a minimum approach of 0.060304 AU from 74.007 years after the grazing event, those

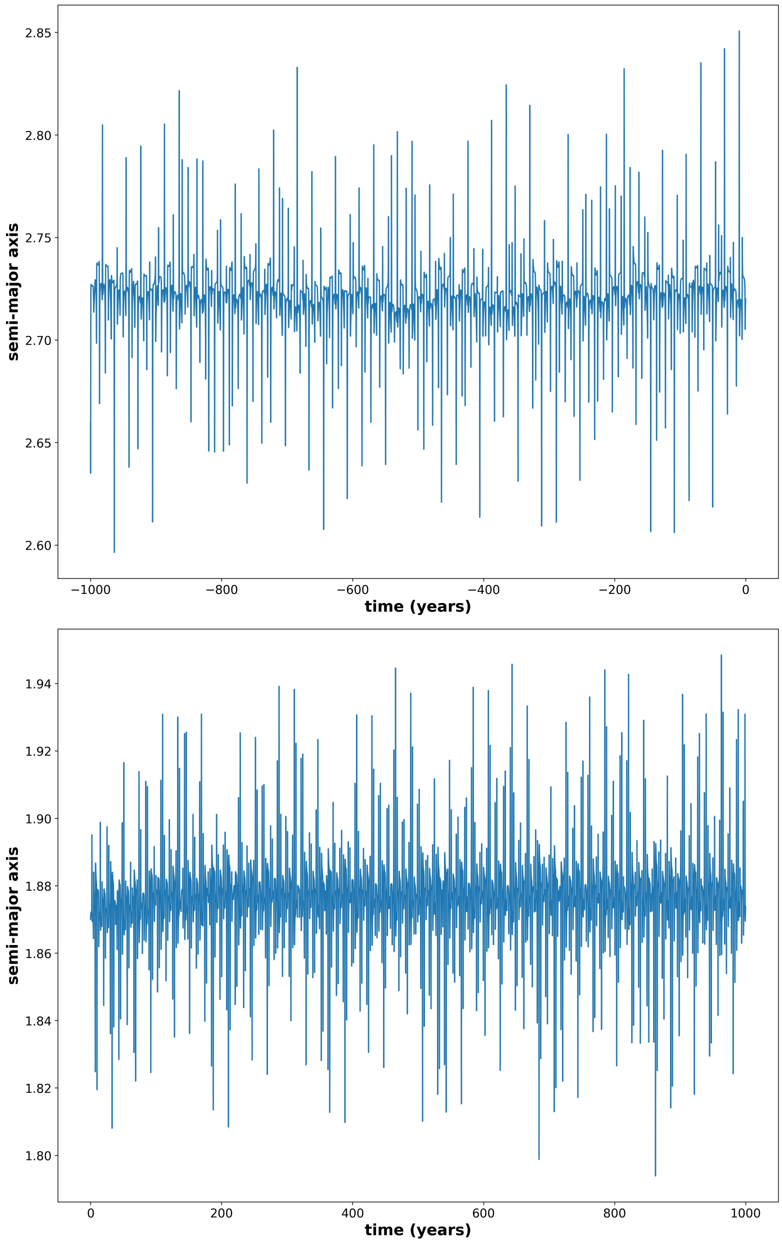


Fig. 7 – The EN131090 meteoroid semi-major axis variations in backward (upper plot) and forward integration (bottom plot) for 1 000 years .

closest distances are plotted in the Figure 8.

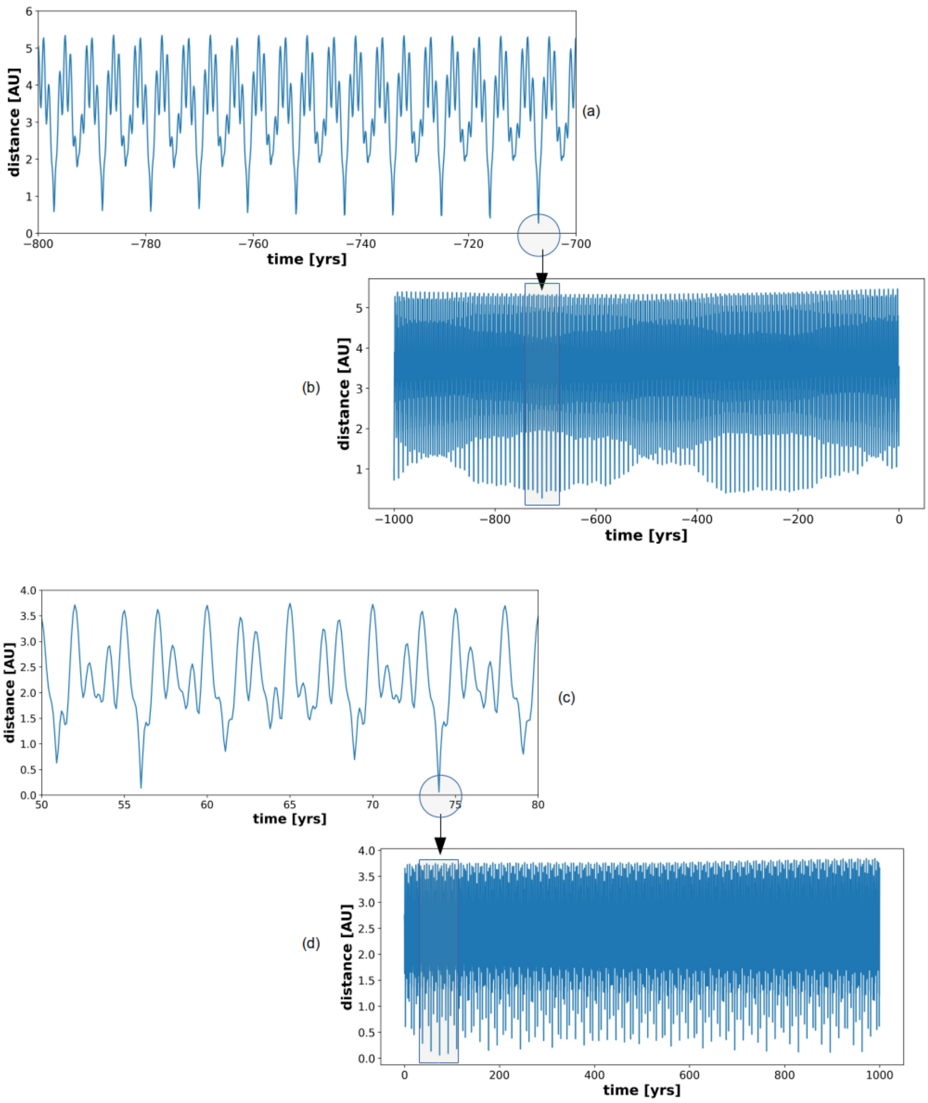


Fig. 8 – The EN131090 meteoroid distance approachs with planet Earth. In Upper plot (a) is a zoomed graph from (b) emphasizing the approach 706.97 years before grazing event, the two bottom plots (c)-zoomed and (d), respectively, show the approach 74.007 years after the grazing event.

## 4. DISCUSSION AND CONCLUSION

Is it possible to predict forward and backwards in time the close approach of a meteoroid, if we observe it as an Earth-grazing fireball?

Approximately every 2.5 years, the EN131090 meteoroid-object returns to the same place in the Solar System around where the 1990 encounter occurred. The period is not known precisely enough to predict when the next encounter between the two will occur.

Using Rebound and symplectic integrators - which are useful in close encounters problems - we studied the before and after orbits of the Earth-grazing fireball EN131090. Modelling and simulating such an observed event we investigated if we can predict the future or the past close approaches of this object with Earth.

Our investigation shows that it is somehow impossible to give an accurate prediction because the object's trajectory could intersect the orbits of other objects, which means that the object's orbit is depending on indeterminate perturbations.

If a small object approaches closer to another object (*i.e.* asteroid, satellite, planet, etc.) at $t_0$, its trajectory will be perturbed, and its orbit after $t_0$ will change. Unfortunately, these unforeseen perturbations made the prediction imprecise.

As described above, NEOs are a real threat for the life on Earth. The geological and biological history of our planet is punctuated by evidence of repeated, devastating cosmic impacts, and as a consequence, asteroid detection is becoming a key topic in astrodynamics. In conclusion, the body's positions at all intermediate steps must be computed in order to arrive at an accurate final configuration.

Furthermore, by systematically observing these Earth-grazing fireballs, carefully storing the data of detailed observations in huge databases, and studying their particular dynamic descriptions, their common behaviour can be recognized in the future with the help of artificial intelligence and machine learning. These tools can aid to better predict the behavior of the objects, and avoid future threats.

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