Earth and asteroid

How to vulgarize complex sciences by using computer science

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Introduction

Asteroids represent a real threat to our planet, although often perceived as distant. Small objects regularly enter Earth's atmosphere, usually without major consequences, but larger bodies could cause regional or even global catastrophes. The Tunguska event in 1908 and the Chicxulub impact, which led to the extinction of the dinosaurs, highlight the potential magnitude of such phenomena.

In response to this risk, the scientific community and space agencies have developed several planetary defense strategies: early observation and detection through telescopes and satellites, numerical trajectory modeling, and even experimental deflection missions such as NASA's DART. However, the effectiveness of these measures also depends on an essential factor: raising awareness and fostering a collective understanding of the issues at stake.

It is in this context that our project was developed, during the 2025 hackathon of the Polytechnic Institute of Advanced Sciences (IPSA), organized as part of the NASA Space Apps Challenge. In just 38 hours, our team designed and prototyped a scientific outreach initiative aimed at raising public awareness of asteroid impact risks and possible solutions. Through interactive and educational tools, this project seeks to strengthen scientific culture, spark interest in space research, and emphasize the importance of preparation in the face of rare but potentially devastating events.

Part 1 - Asteroids and the Risks to Earth: Understanding and Prevention

1.1 Asteroids: Definitions and Characteristics

Asteroids are rocky or metallic bodies orbiting the Sun, primarily located in the belt between Mars and Jupiter. While most pose no threat to Earth, some near-Earth objects (NEOs) pass close to our planet and, in rare cases, could collide with it.

These bodies vary greatly in size, ranging from a few meters to several kilometers in diameter. Their composition, density, and speed directly influence the energy released upon impact, as well as the environmental and societal consequences.

1.2 Risks Associated with Impacts

The consequences of an impact mainly depend on the size and speed of the asteroid:

- **Small objects (<50 m):** usually burn up in the atmosphere, causing moderate aerial explosions, such as the Chelyabinsk event in 2013.
- **Medium objects (50–300 m):** can cause regional destruction and significant environmental effects.
- **Large objects (>1 km):** capable of triggering global catastrophes, including climate and biosphere impacts, as exemplified by the Chicxulub asteroid responsible for the extinction of the dinosaurs.

Impacts are rare, but their potential severity makes prevention and awareness strategies essential.

1.3 Methods of Prevention and Planetary Defense

1.3.1 Detection and Tracking

- Ground-based and space telescopes: detect and monitor NEOs, assessing their size, trajectory, and impact probability.
- Public databases: allow scientists and the public to track potentially hazardous objects.

1.3.2 Deflection and Mitigation

- **Kinetic impact:** missions like the Double Asteroid Redirection Test (DART) altered the trajectory of a small asteroid to demonstrate deflection.
- **Gravitational or nuclear deflection:** theoretical options for large objects.
- **Local emergency plans:** preparation of populations and infrastructures for regional impacts, including drills and alert simulations.

1.4 Importance of Awareness and Scientific Outreach

Even with advanced technical measures, preventing asteroid impacts also relies on collective understanding of the risks. Education and scientific outreach help to:

- Inform the public about the probabilities and consequences of impacts.
- Present existing strategies for planetary defense.
- Encourage interest in space research and support for scientific initiatives.

Our awareness project, developed during the NASA Space Apps Challenge, directly aligns with this goal by providing interactive and accessible educational tools for the general public.

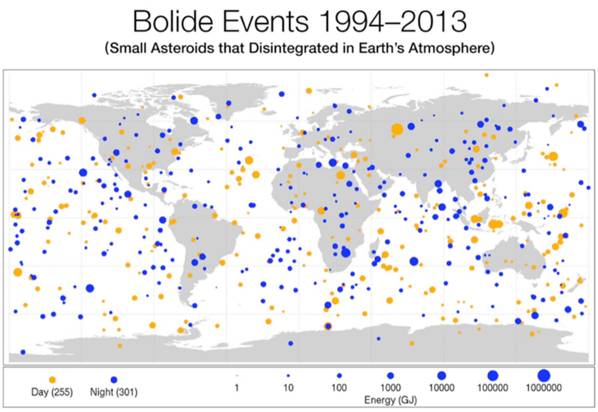

Figure 1: Representation of asteroids that disintegrated in earth's atmosphere

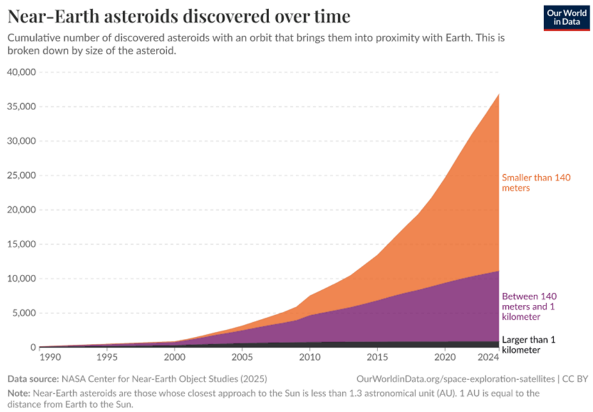

Figure 2: Number of discovered asteroids near earth

Part II — Project Implementation: Simulator, CrashGPT, and Educational Game

2.1 Objectives and Strategy

The main goal of this second part is to present the core operational aspect of our project: the concrete actions taken to reassure the public and popularize complex concepts related to asteroid impacts. Our strategy is based on three complementary pillars:

- **Interactive demonstration:** showing, through simulation and gameplay, the mechanical effects of an impact and the principles of interception.
- **Accessible explanation:** producing simple and reliable explanatory texts for a non-specialized audience.
- **Transparency about limitations:** clearly indicating uncertainties and necessary improvements to avoid misinterpretations.

These principles guided the development of three integrated components of the website: a physical simulator, an explanatory language model ("CrashGPT"), and an educational interception game.

2.2 Impact Simulator

2.2.1 Purpose and Audience

The simulator aims to provide a quantified visualization of the possible consequences of an impact based on adjustable parameters. It is intended for the general public, students, and educators seeking a first understandable estimation without prior knowledge.

2.2.2 Variables and Interface

The user can modify several key variables:

- Mass of the asteroid (kg)
- Size (diameter, m)
- Approach velocity (m/s)
- Approach distance and entry angle
- Target location (selectable on the map)

The interface makes these parameters intuitive (sliders, numeric fields, and a map) and displays synthesized outputs: impact energy (in megatons of TNT), estimated damage zone, explosion height (if atmospheric entry occurs), and simplified risk maps.

2.2.3 Physical Model — Two Phases

The simulator is based on a two-phase trajectory calculation:

1. **Exo-atmospheric phase:** ballistic trajectory governed by initial velocity and gravity. Simplifications ensure coherent estimates without resorting to a full orbital simulation.
2. **Atmospheric phase:** modeling of deceleration due to drag, potential fragmentation, and energy dissipation. The equations incorporate a drag law.

In practice, the trajectory and energy dissipation were first calculated manually and then implemented in a Python script (prompt source) powering the web simulator. This approach ensures that the displayed results come from an identifiable and reproducible physical model.

2.2.4 Degree of Realism and Limitations

The simulator is designed to be plausible: it provides reliable orders of magnitude for educational use. However, it does not replace advanced scientific tools. The main limitations are:

- simplified atmospheric model,
- uncertainty about fragmentation,
- lack of fine hydrodynamic simulation,
- assumptions about the object's composition.

2.3 CrashGPT — An Integrated Explanatory LLM

2.3.1 Functioning

CrashGPT is a large language model (LLM) module integrated into the site. It takes as input the impact configuration (simulator parameters and selected map location) and automatically generates a textual summary. For each scenario, it produces four thematic paragraphs:

1. Impact power (energy and comparison with known references)
2. Estimation accuracy (uncertainties and plausible intervals)
3. Local danger level (effects on population and infrastructure)
4. Recommended measures and practical information (safety advice and educational resources)

Technically, CrashGPT calls a LLM API (such as ChatGPT) and provides it with the simulator's numerical outputs to generate an accessible text.

2.3.2 Educational and Reassuring Role

The purpose of CrashGPT is not to issue alarmist predictions but to contextualize the numbers generated by the simulator, explain why those results occur, and clearly communicate uncertainties. The tone is neutral and educational to reassure non-specialist users.

2.3.3 Current Limitations and Transparency

We observed that the precision of the "accuracy / danger level" paragraphs remains insufficient. The main causes are:

- Insufficient input data to allow the LLM to provide statistically robust estimates (e.g., uncertainty about density, entry angle, fragmentation).
- Probabilistic nature of LLMs: they are excellent at reformulating and explaining, but without solid data, they may produce overly confident or vague statements.
- Lack of calibration between physical outputs and language: numerical data must be transformed into quantitative descriptors that the LLM can use to express uncertainty intervals.

We explicitly display these limitations in the interface to avoid user misunderstanding.

2.4 Educational Interception Game

2.4.1 Educational Objective

The game allows users to pilot a virtual missile to intercept and deflect an asteroid. It illustrates the principles of kinetic interception and deflection (momentum transfer), as well as associated time and energy constraints.

2.4.2 Mechanics and Pedagogy

The player adjusts parameters (interception window, missile delta-v, impact point) and visualizes the trajectory's effect. The game provides instant feedback (success/failure) and short explanations on why an interception worked or not.

2.4.3 Usefulness in the Popularization Strategy

This playful module serves as an experiential bridge between theoretical models and public intuition: by manipulating parameters, users better grasp the temporal and energetic challenges of responding to a potential impact.

2.5 Popularization and Reassurance Actions

To reach our target audience, we combine:

- Simple language free of unnecessary technical jargon.
- Clear visuals (maps, graphs, trajectory animations) accompanying each explanation.
- Indication of uncertainties and practical recommendations (official sources, emergency contacts where relevant).

The tone is designed to inform without alarming: explaining what is known, what is uncertain, and how to interpret the displayed results.

2.6 Improvement Perspectives

To enhance the system's credibility and accuracy, several improvements are planned:

- Data collection: better documentation of average asteroid density/composition and integration of astronomical databases to reduce uncertainty.
- Calibration: performing test runs and calibrating CrashGPT using simulated outputs with known uncertainty ranges.
- Hybrid approach: combining robust physical modeling with statistical methods (Monte Carlo) to produce confidence intervals.

- Atmospheric refinement: replacing the simplified model with more detailed atmospheric physics if the project becomes more scientific.
- UI/UX: improving risk readability and facilitating access to detailed explanations for educators.

2.7 Section Conclusion

This second part describes the concrete achievements of the project: a two-phase physical simulator, a language model (CrashGPT) designed to explain and contextualize results, and an educational game illustrating interception. The focus is on popularization and transparency regarding precision limits. These tools form a coherent set whose educational impact could be further strengthened by improved data integration, calibration, and explicit communication of uncertainties.

Part 3: Asteroid Impact Mitigation Solutions

The Principle of Asteroid Deflection

All asteroid impact mitigation strategies are based on the same fundamental idea: altering the trajectory of the object early enough so that a small change in velocity translates, through the cumulative effect of orbital dynamics, into a large displacement of the impact point on Earth.

There are four main categories of deflection methods:

- Kinetic impactors (direct collision to transfer momentum)
- Nuclear explosion (fragmentation of the asteroid)
- Slow push techniques (gradual alteration of orbit via sustained thrust or gravity)

The most mature approach to date is the kinetic impactor, experimentally validated by NASA's DART (Double Asteroid Redirection Test) mission. DART impacted Dimorphos on September 26, 2022, at a velocity of approximately 6.6 km/s.

The experiment measured a significant reduction in Dimorphos' orbital period around its parent asteroid Didymos by several tens of minutes—demonstrating that a kinetic impact can measurably alter the orbit of a small celestial body.

This result validated the principle and highlighted several key factors to consider:

- Dependence on lead time (the earlier the intervention, the more effective it is)
- Importance of asteroid physical characterization (mass, porosity, shape, and composition)

Momentum Transfer and Physics

From a physics standpoint, the velocity transfer to the asteroid can be approximated by the momentum conservation equation, corrected for ejecta effects:

$$\Delta v_{ast} \approx \frac{\beta\, m_{imp}\, v_{imp}}{m_{ast}}$$

where m_{imp} and v_{imp} are the impactor's mass and velocity, m_{ast} is the asteroid's mass, and $\beta \geq 1$ models the additional momentum contributed by the ejected material.

This relation clarifies two practical insights:

- Increasing the impactor's mass or velocity linearly increases the deflection effect.

- Reducing uncertainty in the asteroid's mass and internal structure (and thus in m_{ast} and β) is critical to accurately predict the actual Δv.

Finally, the available lead time before impact drastically multiplies operational efficiency a very small Δv applied years in advance is often sufficient, whereas an attempt made only months before would become prohibitively costly or even infeasible.

Educational Application: Mission Eligius

Although Mission Eligius is not a technical mitigation solution itself, it serves as a highly effective educational and awareness tool.

By allowing players to simulate the trajectory of a kinetic impactor, adjust velocity, angle, and timing of impact, the game brings to life the real physical principles underlying asteroid deflection.

It illustrates the importance of:

- Early detection of potentially hazardous objects
- Precision in orbital calculations
- Adequate lead time in any planetary defense strategy

From an educational standpoint, Mission Eligius transforms a scientific abstraction orbital mechanics and momentum conservation into an intuitive, hands-on experience. It serves as a form of scientific outreach that helps users grasp the technical and temporal complexities involved in taking effective action.

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