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Research on Space-based Kinetic Impactor Destroying Small-sized Asteroids under Short Warning Time Conditions

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Extended Abstract—

Asteroids with a diameter of less than 50 meters have the characteristics of being numerous, having a high probability of impacting the Earth, and having a short warning time. Although they will not cause global disaster events, they could cause disaster on local areas. This article intends to study the feasibility and plan of destroying the structure of small-sized asteroids by kinetic impact under short-term warning conditions. We first analyzed the characteristics of small-sized asteroids impacting the Earth, pointed out the necessity of kinetic destruction, and combined numerical simulation to study the conditions for kinetic destruction of different types of asteroids; then designed a space-based kinetic interceptor deployment plan to intercept asteroids within a limited warning time and destroy their structure; Finally, through parameter analysis, we studied the factors that affect the ability of kinetic impactors to destroy asteroids and demonstrated their defensive effect against small-sized asteroids.

Background

In 2013, a celestial object measuring approximately 18 meters in diameter disintegrated over Chelyabinsk, Russia, injuring approximately 1,500 individuals and damaging 3,000 homes. If such an impact occurred in a densely populated area, the damage would likely be more severe. Unfortunately, human observation equipment failed to detect the object's arrival in advance. Similarly, in 1908, a small celestial body measuring around 50 meters in diameter struck the Tunguska region of Russia, causing extensive damage to more than 2,000 square kilometers of forest.

Shockingly, 64% of asteroids measuring 140 meters or more in diameter have yet to be cataloged, with that number soaring to 97% for 50-meter-class asteroids and 99% for 20-meter-class asteroids. This indicates that small-sized asteroid impacts, such as the Chelyabinsk incident, which could cause damage on a town-level scale, may be more frequent than previously estimated, and we may be more likely to encounter small-scale asteroid impacts in our lifetime. Currently, asteroid defense research focuses primarily on small celestial bodies of 140 meters, with few studies on asteroids below 50 meters.

For the purposes of this discussion, small-size asteroids are defined as those with diameters ranging from 10-50 meters. There may be as many as one million of these asteroids, making it difficult for humans to catalog all of them in the foreseeable future (see Figure 1). With an absolute magnitude exceeding 24, such asteroids are difficult for human probes to detect well in advance, and can only be spotted using ground-based telescopes when they are sufficiently close to the Earth. Consequently, the early warning time for such asteroids is often very short, sometimes less than 2 years or even just one week. Under these conditions, the use of nuclear explosions is problematic due to safety concerns, and kinetic impact and deflecting the orbit of asteroids may not be realistic since deflection often requires a longer warning time to be effective. Thus, research into short-term intercept missions is necessary.

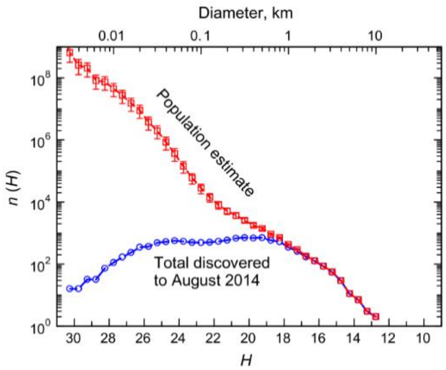

Figure 1 Distribution of the number of asteroids

Currently, the majority of research is concentrated on the defense against near-Earth asteroids with a diameter of 140 meters. However, there is limited research on the defense against smaller celestial bodies with diameters below 50 meters. These smaller bodies are more numerous and have a higher probability of impact and shorter warning times. The field of kinetic destruction remains largely unexplored.

The topic of destroying asteroid structures has been studied for many years and several international seminars have been held to discuss this issue. In 2019, K.A. Holsapple conducted a review of research related to the destruction of asteroid structures and provided energy density requirements for destroying C-class and S-class asteroids with varying diameters (refer to Figure 2). Additionally, at the Seventh Planetary Defense Conference in 2021, B.Barbee stated that a necessary condition for destruction is that the impact velocity increment exceeds ten times the escape velocity from the asteroid's surface.

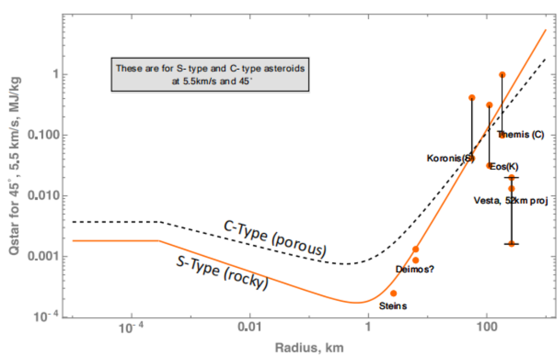

Figure2 Energy density required to destroy an asteroid

We conducted numerical simulations using the iSALE software to verify the research conclusions of K.A. Holsapple in 2019. Our calculations involved a scenario where a 2-ton impactor collided with an S-type asteroid with a diameter of approximately 50 meters and a porosity of 45% at a speed of 7km/s. Our findings confirmed the reliability of K.A. Holsapple's conclusions and demonstrated that it is possible to destroy an asteroid with a diameter of 50 meters and a porosity of 45% using a 2-ton impactor. This provides a theoretical basis for responding to small-sized asteroids within a short timeframe (refer to Figure 3).

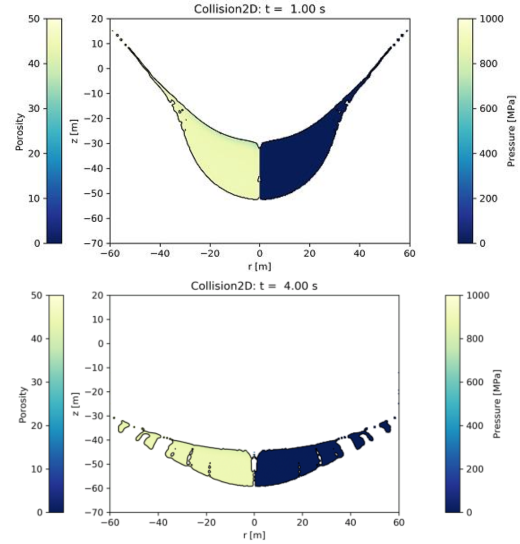

Figure3 Numerical simulation of kinetic destruction of asteroids

To enable rapid interception of asteroids approaching from any direction, we propose pre-deploying kinetic impactors at the L3/L4/L5 points of the Earth-Moon system. Upon detection of an asteroid, a space-based kinetic impactor can be rapidly deployed to intercept the asteroid and provide a swift response to the threat. This approach allows for effective destruction or deflection of the asteroid within a limited warning time. The proposed Earth-Moon Lagrange point interception scheme is illustrated in Figure 4. We conducted simulations on 21 asteroids with diameters ranging from 10 to 50 meters using three mission models and evaluated the defensive capabilities of our constellation under constraints that included a total velocity increment less than 1.2km/s and a warning time not exceeding two years.

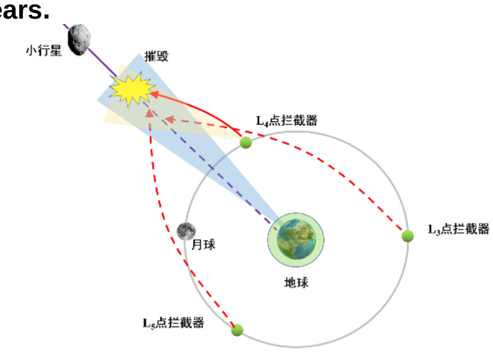

Figure 4 Schematic diagram of the Earth-Moon Lagrange point interception

Purpose of research

The key issue studied in this paper is: firstly, what conditions are necessary to ensure that an asteroid can be destroyed. By analyzing the characteristics of small-sized asteroid impacts and using the iSALE software for numerical simulation, this paper aims to study the energy density required to kinetically destroy asteroids with different properties.

Secondly, a space-based interceptor deployment scheme needs to be designed to efficiently kinetically destroy asteroids within a short warning time. Small-sized asteroids typically have a short warning time before impacting Earth, which means that we need to respond quickly. Under a short warning time, the response system must be fast, timely and efficient in its ability to precisely intercept and effectively destroy an asteroid within a very short timeframe. If ground-launched interceptors are used to destroy or deflect an asteroid, it takes about 5 days just to reach the distance of the Moon from the ground. To ensure safety, disposal must generally be carried out outside of Earth's sphere of influence. Considering orbital transfer time and ground launch preparation time, it is not feasible to launch interceptors from the ground under extreme conditions with only 7 days of warning time. Pre-deploying impactors in orbit for rapid interception of asteroids is the only viable approach. Based on considerations for rapidly intercepting asteroids from all directions, we need our interceptors to be able to quickly intercept an asteroid upon detection and provide a swift response to the threat in order to effectively destroy or deflect it within a limited warning time.

Finally, it is imperative to conduct research on the factors that influence the efficacy of kinetic energy in asteroid destruction. By selecting appropriate asteroids and establishing an interception mission model for simulation purposes, we can optimize the layout of space-based interception constellations by adjusting model parameters. Additionally, we can optimize the interception trajectory from the constellation to the asteroid and calculate key metrics such as the spatial range of interceptable asteroids, time efficiency and diameter of interceptable asteroids. Based on these findings, we can propose specific requirements for spacecraft maneuverability.

Method

This study utilizes the iSALE software to investigate the conditions required for asteroid destruction. The iSALE-2D software employs finite difference methods to analyze a variety of materials and rheological issues. The strength/damage model implemented is the pressure yield model based on skew strain detection proposed by Collins et al. in 2004, while the porosity model used is the Epsilon-alpha model. Within the iSALE software, we have configured the Johnson-Cook strength model as the impactor's strength model and have adopted the Drucker-Prager strength model as the asteroid's strength model. Additionally, an ε-α porosity model has been established for asteroid structure.

This study begins by compiling a comprehensive list of near-Earth asteroids that will make close flybys of Earth between the years 2024 and 2026. After considering various factors such as asteroid size, flyby time, distance and relative velocity, we have selected asteroid 2007 XB23 as our target for investigating extremely short warning times. Asteroid 2007 XB23 is an Apollo-type near-Earth asteroid with an approximate size of 14 meters and a mass of around 4000 tons. Seven days prior to its Earth flyby, this asteroid was situated at a distance of 2.8265 million kilometers from Earth and had a relative velocity of approximately 4.57 km/s.

Subsequently, we identified a total of 21 asteroids with diameters ranging from 10 to 50 meters that will pass within five times the Earth-Moon distance between the years 2031 and 2035 as targets for our investigation on two-year warning times. Simulation analyses were then conducted on these targets.

This study develops an interception mission simulation model and performs orbit optimization to investigate the optimal layout of space-based constellations. In order to achieve rapid response and effective defense capabilities, we have selected the Earth-Moon L3, L4 and L5 points as the deployment locations for our interceptors. A variety of mission sequences have been established, including direct transfer, transfer after sliding and Earth-Moon gravity-assisted transfer (Figure 5). Notably, the Earth-Moon gravity-assisted transfer mode enables us to effectively alter orbital energy while minimizing fuel consumption by leveraging the gravitational forces of both Earth and Moon in conjunction with long-distance transfers between these two celestial bodies. This expands both the temporal and spatial range of our defensive capabilities.

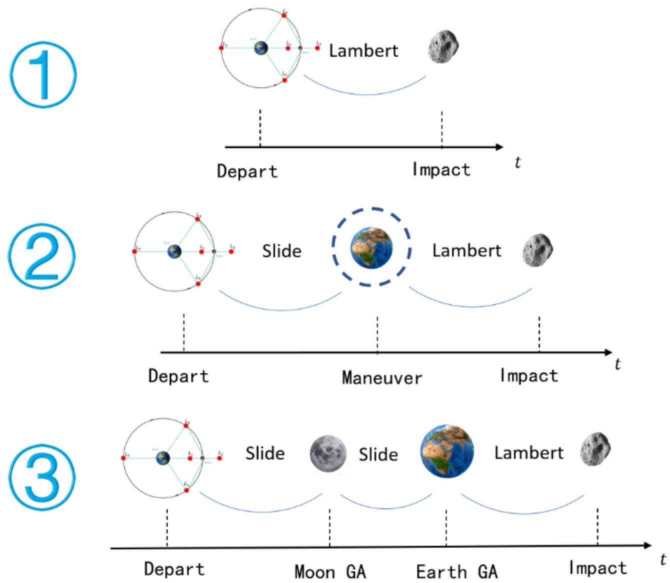

Figure 5 Mission sequences

In addition to the aforementioned efforts, we have also established a high-precision orbital dynamics model of the solar system. This model takes into account gravitational perturbations from planets and moons as well as relativistic effects, as shown in the following equation:

$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{u_{Sun}}{|\boldsymbol{r}|^3} - \sum_{i=1}^{8} u_i\left(\frac{1}{|\boldsymbol{d}_i|^3}\boldsymbol{d}_i + \frac{1}{|\boldsymbol{r}_i'|^3}\boldsymbol{r}_i'\right) + \boldsymbol{a}_{moon} + \boldsymbol{a}_{RE}$$

We have conducted simulations on our mission model by combining global optimization with local optimal search. By varying spacecraft and asteroid mission parameters, we have optimized our model to study the defensive efficacy of deploying interceptors at Earth-Moon Lagrange points. In the direct transfer mode, we have used departure time and impact time as optimization variables. Under the constraints that velocity increments do not exceed 1.2 km/s and impact locations are outside of Earth's sphere of influence, we have optimized for maximum impact crater size as shown in the following equation:

$$\vec{\boldsymbol{X}} = [\boldsymbol{jd}_{depart}, \boldsymbol{jd}_{impact}]$$

$$\boldsymbol{maxmize}\ J(\vec{\boldsymbol{X}}) = r_{Crater}$$

$$\boldsymbol{subject\ to}\ dv < 1.2km/s,\ \mathrm{dis}_{\mathrm{impact}} > 1.5\mathrm{e}6\mathrm{km}$$

In the transfer-after-coasting mode, the interceptor first coasts to the boundary of Earth's sphere of influence before utilizing a Lambert transfer to reach and impact the asteroid. The optimization variables in this mode are departure time $\boldsymbol{jd}_{depart}$, time to transfer to the boundary of Earth's sphere of influence $\boldsymbol{trans}_{2ESOI}$, position at the boundary of Earth's sphere of influence and impact time $\boldsymbol{jd}_{impact}$. Optimization simulations were conducted under the same constraints as mentioned above.

$$\vec{\boldsymbol{X}} = [jd_{depart}, trans_{2ESOI}, RA_{ESOI}, DE_{ESOI}, jd_{impact}]$$

$$\boldsymbol{maxmize}\ J(\vec{\boldsymbol{X}}) = r_{Crater}$$

$$\boldsymbol{subject\ to}\ dv < 1.2km/s,\ \mathrm{dis}_{\mathrm{impact}} > 1.5\mathrm{e}6\mathrm{km}$$

In addition to the aforementioned modes, we have also designed an Earth-Moon gravity-assisted transfer mode. In situations where the warning time is short and the orbital inclination of the asteroid intercepted orbit is relatively high compared to the plane of the Moon's orbit, Earth-Moon gravity assistance can be used to change the orbital inclination with low fuel consumption and successfully complete the interception mission. The spacecraft departs from an Earth-Moon Lagrange point and flies towards its lunar periapsis. After performing a maneuver between Earth and Moon, it flies towards its terrestrial periapsis before using Earth's gravity to slingshot towards the asteroid for interception. The schematic diagram of its orbit and optimization process are shown in Figures 6 and 7 respectively.

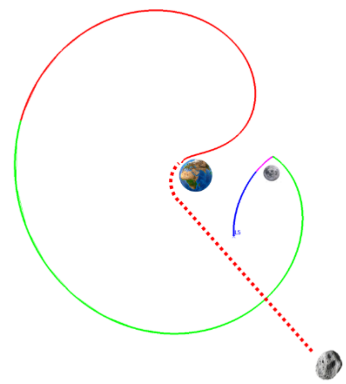

Figure 6 Diagram of Earth-moon gravity-assisted transfer orbit

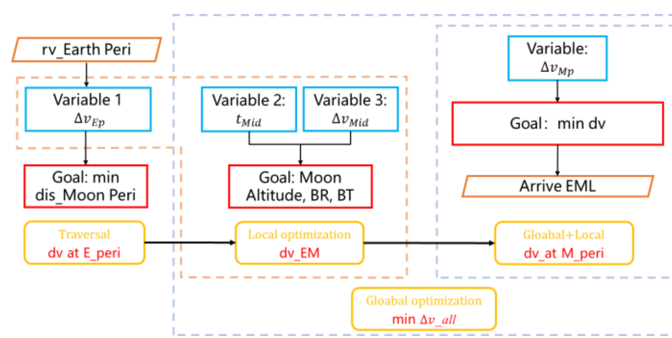

Figure 7 Optimization flow diagram

Results

In the case of extremely short warning times (7 days), preliminary simulations have shown that an interceptor departing from the L3 point can impart a velocity increment of approximately 1532 mm/s to asteroid 2007 XB23 upon impact. This is more than ten times the surface gravitational acceleration of 8.76 mm/s on asteroid 2007 XB23 itself and is sufficient to shatter it. Under these impact conditions,

the maximum diameter of an asteroid that can be destroyed is estimated to be around 28 meters.

In designing interception missions at Earth-Moon lagrange points with a warning time of 7 days, we have assumed that the goal is to maximize impact kinetic energy in order to ensure the destruction of the asteroid. As an example, we have developed an immediate response plan for asteroid 2007 XB23 which has an approximate diameter of 14 meters. Its density is estimated at 2.8 tons per cubic meter and its mass is approximately 4023 tons.

A kinetic interceptor can be launched into an escape trajectory using a Long March 3 rocket with an initial launch mass of 2.3 tons. After transferring to a Lagrange point orbit, the remaining mass is approximately 2 tons. The interceptor can be equipped with a 7500N bipropellant engine with a specific impulse of 315 seconds. Alternatively, it can be equipped with a 2500N engine or multiple 490N bipropellant engines in parallel. Table 1 shows the maximum kinetic energy interception orbits for departures from L3, L4 and L5 points under a warning time of 7 days. Figure 8 shows a schematic diagram of the maximum kinetic energy interception orbit.

Table 1 Maximum kinetic energy interception orbit with 7-day warning time

STARTING POSITION	L3	L4	L5
STARTING TIME	2024-12-4	2024-12-4	2024-12-4
SPEED INCREMENT	2403.46 m/s	3052.29 m/s	2747.84 m/s
TRANSFER TIME	4.72 days	5.02 days	5.13 days
IMPACT DATE	2024-12-9	2024-12-9	2024-12-9
IMPACTOR MASS	0.92 tons	0.74 tons	0.82 tons
IMPACT VELOCITY	6.70 km/s	7.13 km/s	6.86 km/s
IMPACT KINETIC ENERGY PER UNIT MASS	5117.76 J/kg	4703.88 J/kg	4800.07 J/kg

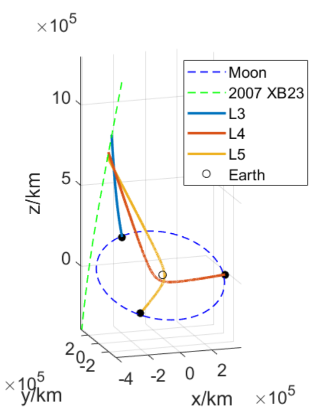

Figure 8 Optimal transfer trajectory of maximum impact energy

Taking the maximum kinetic energy interception orbit starting from L3 point as an example, the interception process is described. The interceptor has an initial mass of 2 tons when it departs from L3 point. After receiving the asteroid warning information, it chooses the timing to start a 7500N engine and ignites for 445 seconds. The velocity increment is 2.4 km/s and consumes 1.08 tons of fuel. After flying for 4.72 days, it hits the asteroid at a distance of 1.02 million kilometers from Earth at a speed of 6.7 km/s (asteroid speed is 4.65km/s and interceptor speed is 2.13 km/s). The impact mass is 0.92 tons and the unit mass impact kinetic energy is 5118 J/kg. The impact can cause an approximately 1532 mm/s velocity increment to asteroid 2007 XB23, which is far greater than ten times its own surface gravitational acceleration of 8.76mm/s and can achieve fragmentation. Under these impact conditions, the maximum diameter of an asteroid that can be destroyed is about 28 meters.

Similarly, interceptors departing from L4 and L5 points can also intercept asteroids with unit mass impact kinetic energies of approximately 4704J/kg and 4800J/kg respectively.

For this asteroid, the interceptor departing from L3 point has higher interception efficiency.

In addition, we have selected 21 real asteroids that will fly close to Earth between 2031 and 2035. Their diameters range from 15 to 50 meters and their perigee distances are less than five times the Earth-Moon distance when they fly close to Earth. With a warning time of two years and a maximum velocity increment set to not exceed 1.2 km/s, we simulated these 21 asteroids.

The results show that spacecraft deployed at L4 and L5 points can complete the impact within two years. The impact can fragment the asteroid with an average velocity increment of only 0.6 km/s. The shortest transfer time is only 40 days and the longest transfer time does not exceed 630 days. The disposal locations are all outside the Earth's sphere of influence (Table 2).

Table 2 Statistics of warning time in 2 years

	DV LIMIT	WARNING TIME	IMPACTABLE ASTEROIDS	POSITIVE DEFLECTIONS	DISRUPTION	EFFECTIVE DISPOSAL	AVERAGE DV
21 ASTEROIDS	1.2km/s	2years	21	4	21	21	608.95m/s

summary and outlook

The research described in this article can provide an innovative solution for defending against asteroids with sizes ranging from 10 to 50 meters under short-term warning conditions. It fills a gap in the relevant field and contributes to human asteroid defense.

In future research, we will refer to real asteroid data to establish a dataset of virtual asteroids impacting Earth. We will use the task model described in this article to perform large-scale simulations on the dataset and believe that we can obtain more meaningful data.

In addition, space-based constellation layouts can also take into account monitoring and early warning. Ground-based telescopes have difficulty observing asteroids approaching from the direction of the sun. Space-based constellation layout interceptors can monitor and warn when no threatening asteroids are detected, making up for the shortcomings of ground-based telescopes. In the future, we will also conduct further research in this area.

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