REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	26.Oct.98	MAJOR REPORT

4. TITLE AND SUBTITLE
VARIOUS METHODS OF PERTURBING THREE ASTEROIDS FROM AN EARTH-IMPACT TRAJECTORY

5. FUNDING NUMBERS

6. AUTHOR(S)
2D LT KULESA RICHARD J

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF COLORADO AT COLORADO SPRINGS

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
98-013

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

VARIOUS METHODS OF PERTURBING THREE ASTEROIDS FROM AN EARTH-IMPACT TRAJECTORY

by

Richard J. Kulesa II

B.S.CoE., New Jersey Institute of Technology, 1997

An investigative report submitted to the Faculty of the Graduate School of the University of Colorado, Colorado Springs, in partial fulfillment of the requirements For the degree of

Master of Engineering in Space Operations

Spring 1998

ABSTRACT

Asteroids with orbits intersecting earth pose varying levels of threat to mankind and our planet. A small object, ~100 m diameter, can wipe out cities the size of New York or San Francisco. Larger objects, > 1 km diameter, impacting the Earth have global, catastrophic consequences. Possible ways of preventing dangerous objects from colliding with Earth are presented in this investigation. Methods of asteroid mitigation fall into two general classes: deflection and fragmentation. Significant work has been done in both areas, but the majority of the numerical results have been for general types (i.e. sizes) of asteroids. This investigation will give numerical results for three real asteroids that get within ~0.04 AU of Earth or closer. Results are produced for a variety of techniques, both deflection and fragmentation, available for hazard mitigation.

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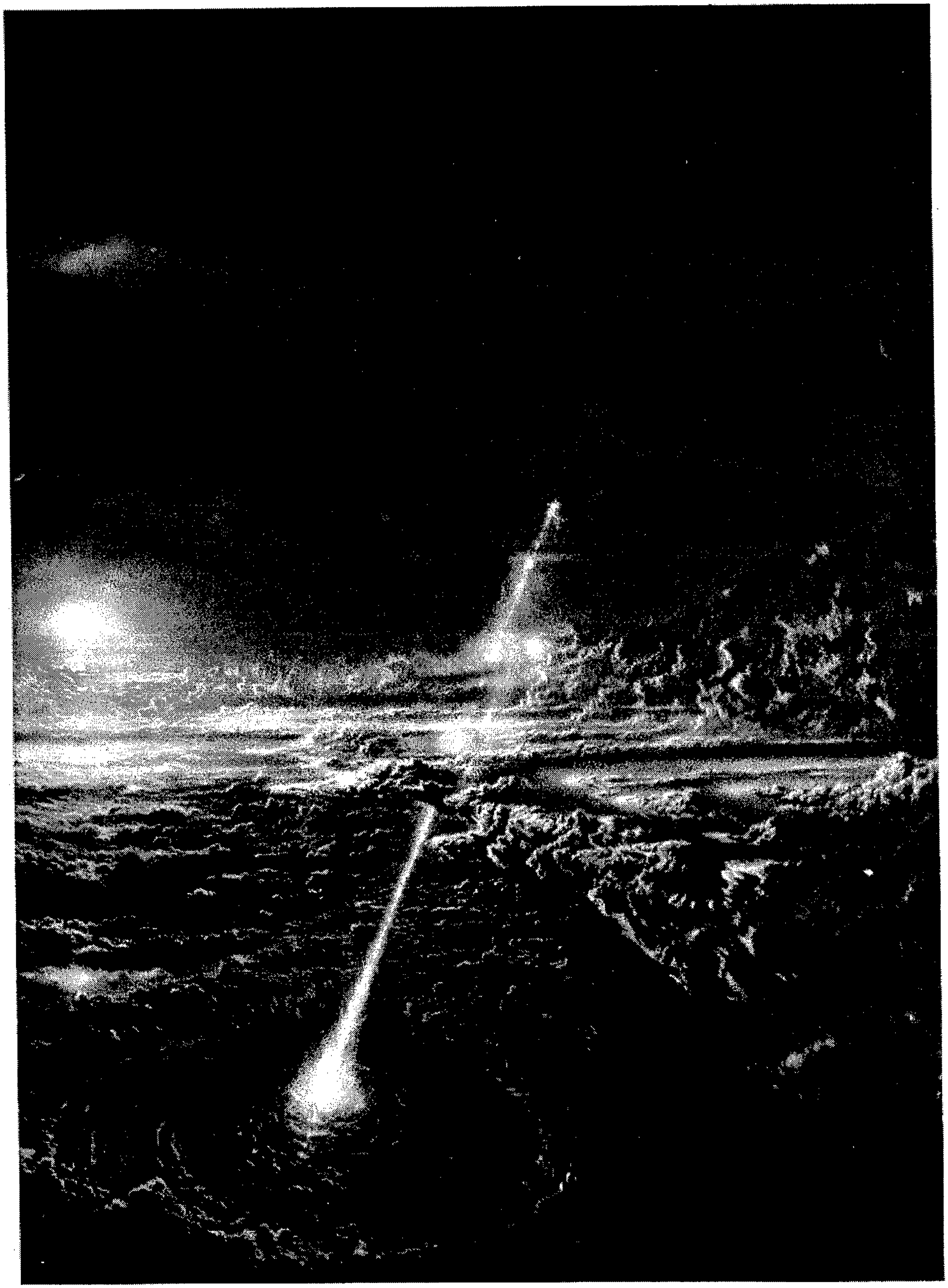


ABSTRACT

Asteroids with orbits intersecting earth pose varying levels of threat to mankind and our planet. A small object, ~100 m diameter, can wipe out cities the size of New York or San Francisco. Larger objects, > 1 km diameter, impacting the Earth have global, catastrophic consequences. Possible ways of preventing dangerous objects from colliding with Earth are presented in this investigation. Methods of asteroid mitigation fall into two general classes: deflection and fragmentation. Significant work has been done in both areas, but the majority of the numerical results have been for general types (i.e. sizes) of asteroids. This investigation will give numerical results for three real asteroids that get within ~0.04 AU of Earth or closer. Results are produced for a variety of techniques, both deflection and fragmentation, available for hazard mitigation.

Contents

Figures

Tables

Background

The remnants of the formation of planets that never got the chance to coalesce into planets race through space at velocities relative to Earth of 5 million ft/min. Some are chunks of dirt, rock, or metal (asteroids); some are sooty balls of ice held together only by gravity (comets).[1] Occasionally, these objects are perturbed into orbits that pass through the paths of Earth and other planets. Exploration of the planets by spacecraft has unveiled crater-scarred surfaces that testify to a bombardment of projectiles that continues today. Even on Earth, where active plate tectonics and erosion rapidly change our landscape, over 140 impact sites have been discovered. About 3.8×10^9 years ago, the initial rain of impacts during planetary accretion ended with the Late Heavy Bombardment. A shower of impacts has continued at an approximately steady rate ever since, with dozens of Earth-crossing asteroids being found each year.[2]

Man has known of Earth crossing asteroids since Reinmuth discovered 1862 Apollo by telescope in 1932. The work by Gilbert on the Meteor Crater, Arizona and following studies made it apparent that the ~140 known impact craters on Earth and virtually all of the craters on the moon were produced by the impacts of Earth-crossing asteroids and comets.[3]

The popular perception by man that asteroids are too remote and unimportant to be of concern was shattered in May and June of 1968. At this time, the media reported news of a close flyby of the asteroid Icarus, then only 6 million kilometers from Earth and travelling at 30 km/sec. The orbit of Icarus was known well enough that impact was not considered probable, but its orbit makes it a recurring long-term threat.[4] The effects of an asteroid or comet hitting the Earth has also become a concern since the publication of the Alvarez *et al.* paper that suggests the Cretaceous/Tertiary (K/T) mass extinction was the result of an asteroid or comet approximately10km across striking the Earth. This hypothesis has been widely accepted since the probable primary impact site has been found in the Yucatan. This impact gave rise to a great extinction of more than 50% of the known genera and probably 90% of all species 65 million years ago. The realization that an impact of an asteroid or comet with Earth could have a catastrophic effect on life took hold in our psyche.[5]

Smaller debris continually strikes Earth's upper atmosphere where it burns up due to the friction imposed on it by air. Meteors, which are typically the size of a marble and have masses of about a gram, can be seen streaking across most clear night skies. Thousands of meteorites weighing a few kilograms penetrate the atmosphere and fall harmlessly to the ground every year. Since the majority of Earth's surface area is uninhabited, the risk of damage by a meteorite is small and there are no known human fatalities by one.[6] The next section assesses the hazards posed by asteroids and comets, referred to collectively as Near-Earth-Objects (NEOs), and introduces the topics that will be reviewed.

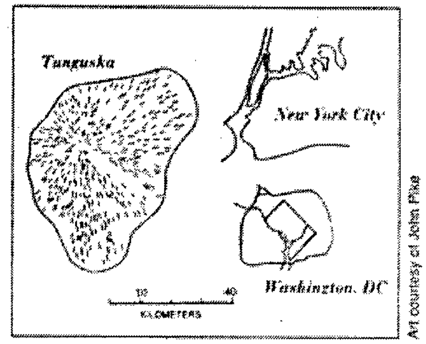
Introduction

Earth-crossing asteroids include rocky and metallic objects evolved from main-belt asteroids that experienced collisional fragmentation; while others are derived from extinct comet nuclei. Most of the Earth-crossers will eventually be ejected from the solar system with the help of Jupiter's gravity. The rest will collide with a terrestrial planet. A third of those collisions will strike Earth.[2] By the end of 1995, 315 Earth-crossing asteroids had been cataloged. The largest is 1036 Ganymed, approximately 41 km in diameter.[7] The cataloging process is far from complete. It is estimated that the degree of completeness for ~1km objects is less than 5%, and for 100 m objects is less than 0.1%. Although the comet flux is only a few percent of the asteroid flux for objects of the same size, comets strike Earth at a much higher velocity than asteroids. Asteroids typically enter our atmosphere travelling at speeds around 20-30 km/sec. Short-period comets typically travel at speeds of 30-40 km/sec, while long-period comets travel at speeds of 50-60 km/sec. Therefore comets have kinetic energies several times greater than asteroids of equivalent size, and constitute a considerable share (approximately25%) of the impact hazard.[2]

The effects of a NEO-Earth collision can be broken down into three broad categories. Small impacting objects have no direct effect on the ground below because most of their energy is dissipated in the upper atmosphere. These are the ordinary meteors or fireballs that can be seen frequently. Once the object reaches sizes over 10 meters, they can pose some threat to humans. The three categories of hazards can be divided based upon size or kinetic energy of the impactor.[8]

1. "Impacting body generally is disrupted before it reaches the surface; most of its kinetic energy is dissipated in the atmosphere, resulting in chiefly local effects."[8]
2. "Impacting body reaches ground sufficiently intact to make a crater; effects are still chiefly local, although nitric oxide and dust can be carried long distances, and there will be a tsunami if the impact is in the ocean."[8]
3. "Large crater-forming impact generates sufficient globally dispersed dust to produce a significant, short-term change in climate, in addition to devastating blast effects in the region of impact."[8]

The size of the impacting body that is described in each category depends upon its density, strength, and velocity. In 1908, a category type 2 event occurred in Tunguska, a region in Siberia. A body, perhaps 60 m in diameter exploded about 8 km above the ground. The energy released is estimated to be in the 12-20 megaton range. The trees in the Siberian forest were mostly knocked to the ground out to distances as far as 20 km from the end of the fireball trajectory. Some trees were snapped in half as far as 40 km away and evidence suggest that fires were ignited up to 15 km from the endpoint by the intense burst of radiant energy. Figure 1. shows some of this devastation. All of these combined effects are similar to those of a comparable nuclear weapon detonated at the same altitude. The only exception is the lack of accompanying bursts of neutron or γ rays, or radioactive fallout.[8]



Tunguska in perspective

Fig 1. Some of the devastation in Siberia from the NEO exploding over the sky. If an equivalent event were to occur in a populated region, hundreds of thousands of people would be killed.[8]

It is interesting to note the average total average impact on Earth estimated by Shoemaker [9] and shown in Figure 2, which gives impact flux as a function of projectile kinetic energy

$$E = .5mv^2$$

Where m is mass in kilograms and v is velocity in km/sec. The equivalent diameter of the NEO is also given assuming a stony-density object striking at 20km/sec. Because of random variability in the process of asteroid and comet break-up upon entering Earth's atmosphere, there is a chance for significant temporal variations in the impact flux. 'Comet showers' could lead to major short-term increases in the impact hazard. In fact, it has been argued that the K/T extinction was due to more than one near-simultaneous impact. For simplification, impacts are treated as occurring randomly in time and space.[2]

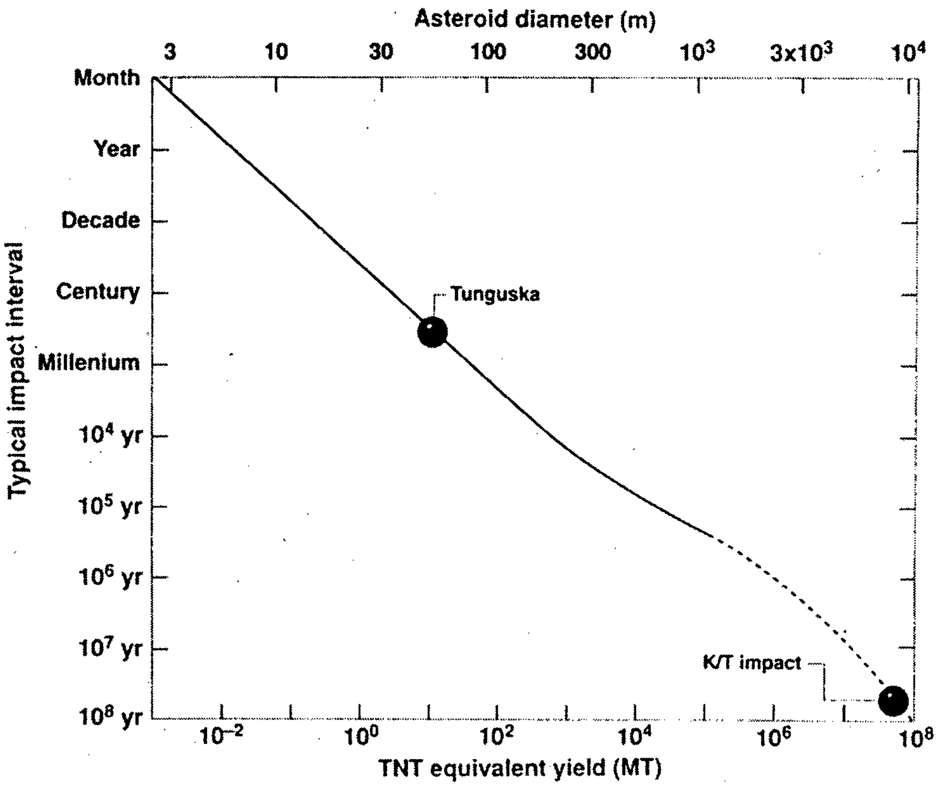


Fig 2. Typical intervals between impacts equal to or larger than the specified yields. The solid line is Shoemakers "best estimate," extended (dashed line) to a minimum estimate of the K/T impact energy. Impact frequencies could be uncertain by a factor of 10 near 0.01MT. The current impact rate is dominated by small number statistics in the region of the dashed line. Equivalent asteroid diameters are shown, assuming 20 km/sec impact velocity and 3 g/cm^3 density.[2]

It is important to find out the size of a NEO that would create a global catastrophe in order to determine if any action is required to avoid a collision with Earth. But first it is necessary to define what a global catastrophe is. Chapman and Morrison define a globally catastrophic impact as one that would disrupt global agricultural production and lead, directly or indirectly, to the deaths of more than a quarter of the world's population. A global catastrophe of this magnitude leads to the breakdown of organized agriculture, but not to the collapse of most natural ecosystems. This is a calamity far greater than the effects of the great world wars, but far smaller than the K/T impact. Chapman's and Morrison's definition considers a catastrophe that would destabilize modern civilization, but not an apocalypse that would threaten the survival of our species.[2]

A thorough investigation into the threshold for a global impact catastrophe by Toon yields results to this question.[10] He required the impact to create an optical depth greater than2, which is produced by sub-micrometer dust that is injected into the stratosphere. This effect will lower average land temperatures by several, to perhaps 10° C or more, for a period of months. This will lead to frosts in mid-latitudes, even in summer. Such an environmental shock will stop agriculture for at least one growing season. Compounded by the other effects of the impact, such as direct killing of millions, destruction of the ozone layer, widespread acid rain, and so on, the agricultural disaster would precipitate the collapse of global economic, social, and political structures.

Based on nuclear weapons tests and data from the K/T extinction, Toon found that an optical depth of ≈ 2 would result from a groundburst with a yield of 10^5-10^6 MT.[10] This corresponds to a diameter of 1-2km for a stony object striking at 20 km/sec. Uncertainties in the threshold energy probably exceed an order of magnitude above or below. This is due to lack of information on the effects of physical stresses on ecosystems in the context of a 'impact winter'. To account for those and other associated uncertainties (physical and chemical effects), Chapman and Morrison give a range of thresholds from 1.5×10^4 to 10^7 MT. These values are shown in Table 1. They discuss the range of uncertainties in a journal entry to *Nature*.

> "It would take a very unfavorable combination of parameters coupled with an assumption that human society is very fragile, to imagine that an object with a diameter of ≤ 0.5 km could produce global catastrophe; on the other hand, an object

greater than 5 km would create a global firestorm and so much darkness from stratospheric opacity that vision would cease-an environmental holocaust certainly exceeding any definition for the onset of global catastrophe."[2]

Table 1. Thresholds for global catastrophe.

	Energy (MT)	Asteroid diameter (km)	Comet diameter (km)	Typical interval (yr)
Lower Limit	1.5×10^4	0.6	0.4	7×10^4
Nominal	2×10^5	1.5	1.0	5×10^5
Upper Limit	1×10^7	5	3	6×10^6

This investigation looks at the energy requirements for perturbing the orbits of three asteroids in order to deflect them from an Earth impact. My research has come across no sources that have done analysis on actual asteroids that pass close to earth. Instead, previous work has been done on general sizes of asteroids. Doing work on actual asteroids gives more depth to the results presented. Table 2 lists the three asteroids this investigation gives results for. Don Yeomans of the NASA/Caltech Jet Propulsion Laboratory [11] did the predictions that estimate the date and distance of the closet approaches. David Tholen of the University of Hawaii supplied the NEO diameter estimates.[7] Other asteroid data is presented in the appendix.

Table 2. The three NEO's presented in this investigation.[11],[7]

Object Designation	Approximate date of closet approach	Closet approach distance to Earth (AU)	Approximate diameter (km)
1991 RB	1998 09 18.475	0.0401	0.6
1991 VH	2008 08 12.238	0.0291	1.5
3122 Florence	2017 09 1.493	0.0472	6.0

These NEO's are in no real danger of striking Earth, but could pose a long-term threat if their orbits were to pass closer and closer to Earth. Research of their long-term paths have only been done up to 2020. The three NEO's (all asteroids) also make up the three ranges that compose the global catastrophe threshold previously presented. If 3122 Florence were to strike Earth, life as we know it would end. On the other hand, a collision with 1991 RB would take a series of circumstances and assumptions to create a global catastrophe.

I consider several strategies for both deflecting and fragmenting these NEO's. These strategies use devices that encounter the NEO many years or decades before their projected Earth impact. Solem has discussed short warning responses, which might be necessary for new comets, in his work at the Los Alamos National Laboratory.[12],[13] The deflection strategies include the following: firing a large mass to strike the NEO, a ejecting mass from the NEO (a mass driver), attaching a solar sail to the NEO, and "painting" the surface of the NEO. Nuclear explosions can also be used to deflect the NEO through the influence of radiation from a nearby denotation or by the impulse imparted by ejecta from a catering explosion on the asteroid surface. Fragmentation accomplished with nuclear devices is also explored.

NEO's can be deflected from Earth-crossing orbits by inducing perturbations that are perpendicular to or along the direction of motion. This will cause the NEO's orbital velocity to either speed up or slow down in relation to the Sun. If a Δv is applied transversely to a circularly orbiting NEO, a eccentricity or inclination is induced. This results in an oscillation about the original orbiting point of amplitude

$$\delta l \approx \frac{\Delta v}{v_0} a \tag{1}$$

where δl is the distance perturbed, v_0 is the orbital velocity in relation to the Sun (30 km/sec for the Earth), and a is the semi-major axis.[14] To perturb a NEO by $\delta l \approx 1$ Earth radius, $R_\oplus$, the Δv required is

$$\Delta v \approx \frac{v_0 R_\oplus}{a} \approx 1 \text{ m/sec} \tag{2}$$

This approximation works for all three of the NEO's presented in this paper. For the rest of the calculations, we would like to perturb a NEO's orbit by 20 $R_\oplus$, instead of 1. This is a more realistic approach to deflecting the NEO for the reason that a NEO need not be aimed directly at Earth to cause a problem. The Earth's gravity field will "bend" a NEO's trajectory slightly as it gets close, so that a "near miss" may result in a collision. Therefore the "capture area" of the Earth is several times larger than its actual area, and for this reason 20 $R_\oplus$ will be used. Some researchers have used a deflection width of 1 $R_\oplus$, which seems much to close to avoid impact.[14] Ahrens *et al.* suggest that to perturb a NEO on a time t short compared with the orbital period, a simple linear estimate suffices;

$$\delta l = \Delta v t \tag{3}$$

To perturb a body by 20 $R_\oplus$ in time t requires

$$\Delta v \approx \frac{20 R_\oplus}{t} \approx \frac{4}{t} \text{ m s}^{-1}\text{/year} \tag{4}$$

Ahrens *et al.* also predict that the linear estimate reduces to the orbital oscillation after approximately 1 radian of orbital motion.[14]

Velocity changes applied parallel to the orbital motion changes the semi-major axis. This results in a change of the period where the period, T, is

$$T = 2\pi \sqrt{\frac{a^3}{\mu_{sun}}} \tag{5}$$

The velocity change will create a long-term drift of the NEO from its original path.[14] For a NEO with a circular orbit, the mean drift velocity, $\Delta v'$ is in the opposite direction of the Δv and larger.

$$\Delta v' = -3\Delta v$$

An even larger drift velocity will occur if the impulse is utilized at the perihelion of an eccentric orbit. For a NEO whose eccentricity is 0.5, $\Delta v' \approx -5\Delta v$.[14] Instead of perturbing a body on a time t short compared with the orbital period, we now perturb the body over a time t long compared with the orbital period.

$$\delta l = 3\Delta v t$$

$$\Delta v \approx \frac{20R_{\oplus}}{3t} \approx \frac{1.4}{t} \text{ m s}^{-1}\text{/years} \tag{6}$$

This yields the conclusion that with enough time, about a decade, we could divert a NEO from a collision course with Earth using a Δv as small as approximately 0.14 m/sec. It also suggests that an impulse applied parallel to the orbital motion requires less Δv than an impulse applied transversely.[14] Figure 3 illustrates this point. The rest of this investigation is dedicated to finding the requirements necessary to produce a Δv of 0.14 m/sec through the previously mentioned methods. Unless otherwise noted, it is assumed that the Δv is applied parallel to the direction of motion and that we will move it 20 $R_{\oplus}$.

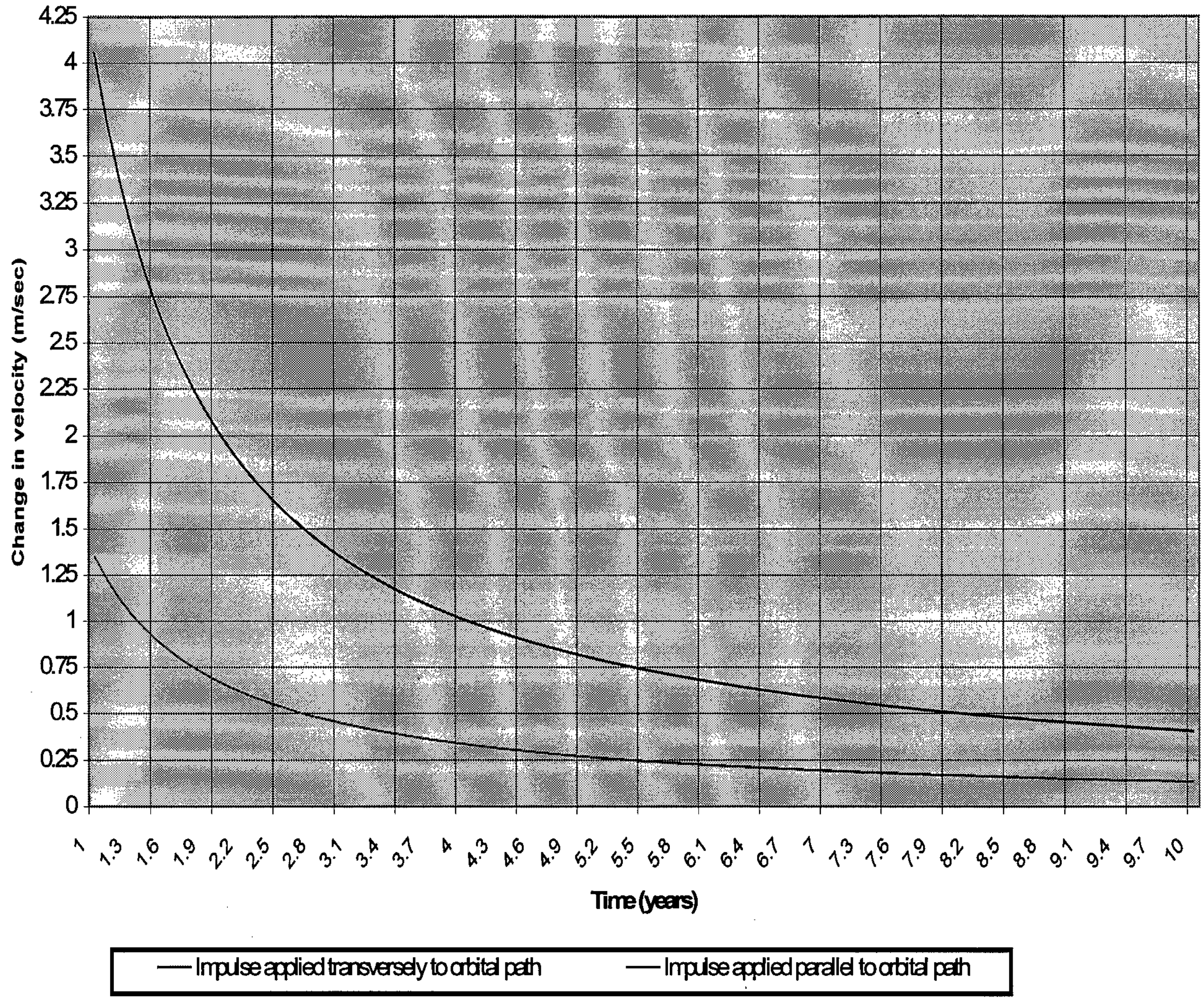


Fig 3. Δv requirements to move a NEO 20 $R_\oplus$ based upon the direction of the impulse.

Specific Topics of Review

The methods of asteroid hazard mitigation for the Earth will now be reviewed. The information is primarily a review of work done by Ahrens *et al.* and Ivaashkin and Smirnov. I have manipulated their work to do an investigative analysis for three real asteroids. Table 3 lists these asteroids, their approximate size and mass, assuming they are spheres with a density of 2 g/cm^3. The problem of asteroid hazard mitigation for Earth is extremely difficult and the results that will be presented are preliminary and should only be used for comparative analysis.

Table 3. Approximate mass of the three NEOs being investigated.

Object Designation	Approximate diameter (km)	Assumed density (g/cm^3)	Approximate mass (kg)
1991 RB	0.6	2.0	2.262×10^{11}
1991 VH	1.5	2.0	3.534×10^{12}
3122 Florence	6.0	2.0	2.262×10^{14}

Direct-impact deflection

The first method to be investigated is firing a large mass at the asteroid. This will place an instantaneous correction of the asteroid's heliocentric velocity vector. Changing its kinetic energy results in a change in the trajectory. The spacecraft that will collide with the NEO is assumed to have a flight trajectory that is half of a Hohmann transfer ellipse. Other assumptions include the Earth having a circular orbit with a radius $r_{\oplus} = 1$ AU.[15] Figure 4 shows this geometry. The mass of the spacecraft in orbit is equal to 181,500 kg (approximately 200 tons) and travels in a circular orbit with $r_o = 6678$ km. The aphelion ($r_{a,as}$) and perihelion ($r_{p,as}$) distance of each investigated NEO is Table 4.

Table 4. Aphelion and Perihelion distances of the three NEOs being investigated.[7]

Object Designation	Semi-major Axis (AU)	Eccentricity	Aphelion distance (AU)	Perihelion distance (AU)
1991 RB	1.4502	0.4839	2.1520	0.74844
1991 VH	1.1363	0.1437	1.2996	0.97301
3122 Florence	1.7685	0.4227	2.5160	1.0210

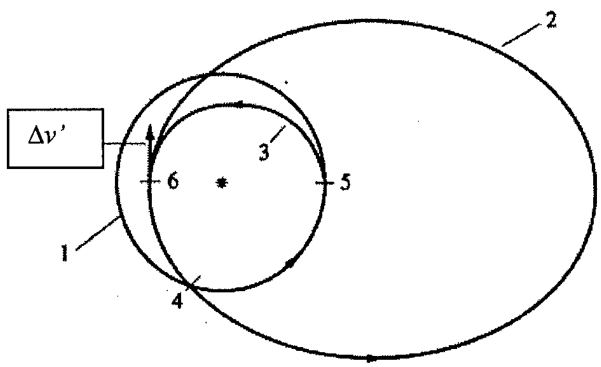


Fig 4. The spaceflight trajectory from the Earth to the perihelion of the NEO orbit in case of impact influence on asteroid: 1, the Earth orbit; 2, the NEO orbit; 3, spacecraft orbit; 4, NEO-Earth encounter point; 5, point of spacecraft start from the earth; 6, NEO-spacecraft collision point.[15]

The following is the algorithm of the velocity impulse applied to an asteroid by a spacecraft impact. When the spacecraft leaves Earth orbit, it has a exhaust velocity (specific impulse of thrust) of $c_1 = 4.5$ km/sec.[15] The spacecraft will then have a mass at the moment of its collision with the NEO of

$$m_{sc} = m_0 e^{-\left(\frac{\Delta v_1}{c_1}\right)} \qquad (7)$$

Δv_1 is the value of the velocity impulse applied to the spacecraft to start from its LEO orbit.[15] It equals

$$\Delta v_1 = \left(v_\infty^2 + 2\frac{\mu_\oplus}{r_0}\right)^{1/2} - \left(\frac{\mu_\oplus}{r_0}\right)^{1/2} \qquad (8)$$

where $\mu_\oplus$ is the gravitational parameter of the Earth and v_∞ is the spacecraft geocentric velocity "at infinity".[15] v_∞ can be expressed in terms of

$$v_\infty = \left|\bar{v}_{a,sc} - \bar{v}_\oplus\right| \tag{9}$$

Here $\bar{v}_{a,sc}$ and $\bar{v}_\oplus$ are the geocentric velocities of the spacecraft at aphelion and the Earth at the start of the transfer, respectively. The collision of the spacecraft is assumed to be non-elastic when it impacts the asteroid.[15] The drift velocity that was described in the introduction is

$$\Delta v' = \frac{m_{sc}}{m_{ast} + m_{sc}}(\bar{v}_{sc} - \bar{v}_{ast}) \tag{10}$$

Here $\bar{v}_{sc}$ and $\bar{v}_{ast}$ are the heliocentric velocities of the asteroid and spacecraft moments before they collide, respectively. In the model, the velocities are taken at perihelion of both orbits.[15]

The change in the velocity of the asteroid causes a small displacement at its perihelion. The displacement value approximately equals the minimal distance of the NEO from the Earth at the time of collision. The displacement is perpendicular to the orbit and its value is described by

$$\delta l = v_{p,ast} n \delta T \tag{11}$$

where δT is the very small change of the asteroids period due the velocity applied by spacecraft. δl grows linearly by n orbital revolutions after impact.[15] The expression for T was described in equation 5 and the energy integral is

$$v_p^2 - \frac{2\mu}{r_p} = -\frac{\mu}{a} = -\frac{2\mu}{(r_p + r_a)} \tag{12}$$

where a is the semi-major axis of the asteroid orbit and μ is the gravitational parameter of the Sun.[15] This expression, along with the equation for T, help to find the following modifications:

$$\delta T = \frac{3T}{2a}\delta a, \qquad 2v_p \Delta v_p^{'} = \frac{\mu}{a^2}\delta a \tag{13}$$

Substituting the new δT into the previous expression and then substituting δa into δl yields

$$\delta l = \frac{3nTv_{p,ast}\delta a}{2a} = \frac{3nTv_{p,ast}^2 a\Delta v_p^{'}}{\mu} \tag{14}$$

Finally, substituting in values for $v_{p,ast}$ gives

$$\delta l = \frac{3nTr_a \Delta v_{p,ast}^{'}}{r_p} \tag{15}$$

where $\Delta v'_{p,ast}$ was previously obtained from equation 10. If we solve for v_p and v_a, the last two expressions, v_∞ and (v_{sc}-v_{ast}), can be resolved. To do this we go back to the energy integral and solve for v.[15]

$$v_p = \left(\frac{2\mu}{r_p}\right)^{1/2} \bullet \left(\frac{r_a}{r_p + r_a}\right)^{1/2}$$

$$v_a = \left(\frac{2\mu}{r_a}\right)^{1/2} \bullet \left(\frac{r_p}{r_p + r_a}\right)^{1/2}$$

Now the velocity of the spacecraft from the Earth is

$$v_\infty = \left(\frac{\mu}{r_\oplus}\right)^{1/2} \bullet \left[\left(\frac{2r_{p,sc}}{r_{p,sc} + r_{a,sc}}\right)^{1/2} - 1\right] \tag{16}$$

and the velocity of the collision between the spacecraft and the asteroid is

$$\left|\bar{v}_{sc} - \bar{v}_{ast}\right| = \left(\frac{2\mu}{r_{p,ast}}\right)^{1/2} \bullet \left[\left(\frac{r_{a,ast}}{r_{p,ast} + r_{a,ast}}\right)^{1/2} - \left(\frac{r_{a,sc}}{r_{p,sc} + r_{a,sc}}\right)^{1/2}\right] \tag{17}$$

Using the data of the three NEOs, I did an analysis to see how much $\Delta v'$ is produced when a spacecraft approximately 200 tons strikes the NEO at perihelion. Along with that analysis, I found how long it would take to move the NEO 20 $R_\oplus$ with the given $\Delta v'$. A second analysis was done to see how large a spacecraft would be needed to move each NEO in approximately 10 years. Table 5 and 6 list the results.

Table 5. Results of an impact of a NEO with a approximately 200 ton spacecraft.

	1991 RB	**1991 VH**	**3122 Florence**
Mass of spacecraft (kg)	181,500	181,500	181,500
Mass of NEO (kg)	2.262×10^{11}	3.534×10^{12}	2.262×10^{14}
v_∞ (km/sec)	2.226	0.204	0.155
$\lvert \bar{v}_{sc} - \bar{v}_{ast} \rvert$ **(km/sec)**	5.117	1.891	5.529
Δv_1 (km/sec)	3.425	3.202	3.201
Mass of s/c @ impact (kg)	84,795.4	89,093.5	89,109.59
$\Delta v'$ (cm/sec)	0.1918	0.004767	0.0002178
Period of NEO, T (years)	1.7465	1.2113	2.3519
nT , time to move NEO 20 $R_\oplus$ (years)	**244.28**	**21,161.12**	**251,027.6**
N, number of revs to move NEO 20 $R_\oplus$	140	17,470	106,735

Table 6. Mass of spacecraft needed to move NEO's in approximately 10 years.

	1991 RB	**1991 VH**	**3122 Florence**
Mass of NEO (kg)	2.262×10^{11}	3.534×10^{12}	2.262×10^{14}
nT , time to move NEO 20 $R_\oplus$ (years)	11.08	10.97	10.12
N, number of revs to move NEO 20 $R_\oplus$	7	10	5
v_∞ (km/sec)	2.226	0.204	0.155
$\lvert \bar{v}_{sc} - \bar{v}_{ast} \rvert$ **(km/sec)**	5.117	1.891	5.529
Δv_1 (km/sec)	3.425	3.202	3.201
Mass of s/c @ impact (kg)	1.8688×10^{6}	1.7181×10^{8}	2.2093×10^{9}
$\Delta v'$ (cm/sec)	4.228	9.183	5.400
Period of NEO, T (years)	1.7465	1.2113	2.3519
Mass of spacecraft (kg)	**$\sim 4.00 \times 10^{6}$**	**$\sim 3.50 \times 10^{8}$**	**$\sim 4.50 \times 10^{9}$**
Mass of spacecraft (tons)	~ 4409	~ 385,800	~ 4,960,400

It is obvious from the tables that impacting a NEO of these magnitudes with a spacecraft is not the quickest or easiest method for mitigating the hazard. Even considering that we would have several centuries notice of the hazard, using a spacecraft of 200 tons may not be reasonable. The only other way of reducing the time, nT, would be by having more accurate knowledge of the NEO motion near Earth in order to lower the 20 $R_\oplus$ requirement.

Mass drivers for deflection

Another method of deflection, that would also be long-term, would be to land a spacecraft on the NEO and perturb its orbit. The spacecraft can accomplish this by removing mass from the NEO and ejecting it into space. The ejecta throw-off from the removal would perturb the orbit, but would have to have greater than escape velocity.[14] If we assume a lead time of three decades, the velocity change required would be (from equation 6)

$$\Delta v \approx \frac{20R_\oplus}{3t} \approx \frac{1.4}{t} \approx \frac{1.4}{30} \approx 4.7\ \text{(cm/sec)/year}$$

This possibility, explored by Ahrens *et al.,* is to deliver a reaction engine or 'mass driver' to the NEO which would mine or eject the material from part of the asteroid. It could provide the need perturbation if the NEO is not too large.[14] For an ejection velocity of 300 m/sec, the mass necessary to produce a recoil of 4.7 cm/sec would be

$$\Delta m \approx \frac{\Delta v}{v_{esc.}} m_{ast} \approx \frac{4.7 cm/\sec}{300 m/\sec} m_{ast}\ \text{kg/year} \tag{18}$$

Δm becomes 0.47% of the mass of each NEO presented in this investigation. The results for the three NEOs are listed in Table 7.

Table 7. Ejected mass necessary to perturb NEOs 20 $R_\oplus$ in 30 years

Object	Mass of NEO (kg)	Δm (kg/year)	Δm total (kg)
1991 RB	2.262×10^{11}	3.545×10^{7}	1.06×10^{9}
1991 VH	3.534×10^{12}	5.537×10^{8}	1.66×10^{10}
3122 Florence	2.262×10^{14}	3.545×10^{10}	1.06×10^{12}

This method could be technically feasible in the future as long as some large roadblocks are overcome. The mass driver must have enough energy to eject the material from the NEO and the means to do it. This is also considering that the spacecraft can land on the NEO undamaged and in the proper position to operate. Finally, it would have to eject the material at escape velocities and be able to operate continually for many, many years.

Deflection by nuclear explosion radiation

This next method of perturbing an asteroid's orbit is the creative product of technical discussions held at the NASA workshop [16] on Near Earth Object Interception, 14-16 January 1992, and reported by Ahrens *et al.* 1992. It involves detonating a nuclear explosive above a NEO whose yield is predominately in the form of neutrons. The NEO will have a large portion of its surface irradiated. The irradiated surface material subsequently expands and falls away from the asteroid at speeds greater than the escape velocity (hopefully) and a decaying stress wave travels through the NEO. The blow-off of the irradiated shell induces a velocity perturbation in the NEO that will move it out of a collision course with Earth after a period of time.[14] Figure 5 illustrates this process.

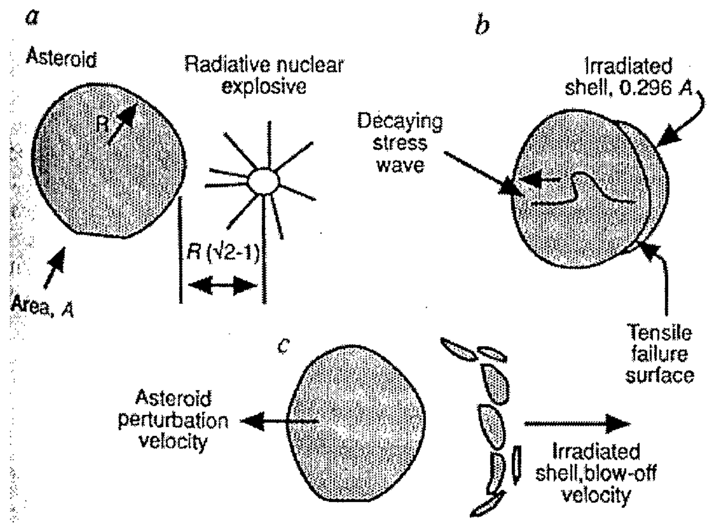


Fig 5. How nuclear explosive radiation could be used to induce a velocity perturbation of approximately 14 cm/sec in a near-Earth asteroid. A), Nuclear explosive designed to provide a substantial fraction, z, of its yield as energetic neutrons and γ-rays is detonated at an optimum height above an asteroid. B) Irradiated to a depth of approximately 20 cm, surface material subsequently expands and spalls away from the asteroid, inducing a stress wave of several kilobars amplitude in the asteroid. C), Blow-off of the irradiated shell induces a velocity perturbation of approximately 14 cm/sec in the asteroid. [14]

Studies have shown that the optimal height of a nuclear explosion to induce the maximum irradiation of a surface should be equal to

$$h = \left(\sqrt{2} - 1\right) R_{ast} \tag{19}$$

where h is the altitude of the explosion above the NEO and R_{ast} is the radius of the asteroid.[17] Studies have also shown that a maximum dose of f_{max}=0.3 times the total radiative yield is delivered to 0.3 times the unit area of a spherical asteroid.[14] Ahrens *et al.* concluded that for a mean neutron cross-section of 10^{-24} cm^{-2}, an assumed asteroid density of 2 g/cm^3 and a mean atomic weight of 25, a neutron penetration depth of approximately 20 cm can characteristically be achieved.[14]

Another assumption is that the fraction, $z = 0.03$, of the explosive yield is delivered as neutron or other radiation. This radiation is completely converted to internal energy, ΔE, per unit mass in the irradiate shell.[14] The energy per kiloton of explosive yield delivered to the irradiated shell is

$$\Delta E = f_{\max} z(4\text{x}10^{19}) \text{ erg} \tag{20}$$

where 4 x 10^{19} is the number of ergs found in one metric kiloton of explosive yield.[14] Ahrens *et al.* predict that the irradiation will induce an average temperature rise of less than 10^2 Kelvin. This heating at a constant volume of the shell will result in an increase in the pressure (per kiloton nuclear explosive yield) of

$$\Delta P = \gamma \rho \Delta E \tag{21}$$

where γ is the thermodynamic Gruneisen ratio, here assumed to be unity (1.0). ρ is the NEO density, previously assumed to be 2.0 g/cm^3.[14] This irradiation occurs less than approximately 10^2 μs required for the sonic wave to travel through the shell. From the previous equation, this energy density will raise the shell thermodynamic pressure to approximately 1.7 kbar (per kiloton of nuclear explosive yield). As depicted in Figure 5, this pressure accelerates the irradiated shell to the right, and a stress wave pulse is propagated to the left within the asteroid. The right-moving irradiated shell and left propagating stress wave cause the shell to break away from the asteroid to conserve momentum. The stress wave that propagates through the NEO is of low enough amplitude not to produce any further destruction.[14] By assuming a compressional wave velocity, c_p, of 2 km/sec in the NEO material, Ahrens *et al.* find that the resulting outward particle velocity of the irradiated shell is

$$\Delta v_r = \frac{\Delta P}{\rho c_p} = 44 \text{ m/(sec kton)} \tag{22}$$

Since the only component of velocity that will be considered is along the direction between the explosive and the asteroid center, the velocity of the irradiated shell is reduced to approximately

31m/(sec·kton).[14] Table 8 lists the perturbation velocity, acquired by conservation of momentum, for each NEO.

Table 8. Detonation sizes required to move three NEOs 20 $R_\oplus$ in 10 years.

Object	Perturbation velocity cm/(sec·kton)	Deflection velocity required (cm/sec)	Optimum height of detonation (meters)	Size of Nuclear Explosion required
1991 RB	~1.5	14	124.3	~9.3 kton
1991 VH	~9.5 x 10^{-3}	14	310.7	~1.47 Mton
3122 Florence	~1.5 x 10^{-4}	14	1242.6	~93.3 Mton

This type of orbital diversion would require detonations of magnitudes that already exist. The required size of the nuclear explosion can be further reduced if the amount of time needed to move the NEO is increased from the current 10 year assumption.

Deflection by surface nuclear explosive

Another method that involves nuclear explosives is detonating a nuclear weapon on the surface in order to form craters on the NEO. This investigation will not go into too much detail of this method because of the extreme complexity. I will present concise conclusions of this method as presented in NASA Contractor Report 190116.[18] Another reason for the lack of detail is that this method is, at best, has results that are no better than radiative standoff explosions with requirements that are more uncertain.

The material that is ejected from the surface explosion creates a velocity change in the NEO, which will move its orbit away from the Earth. The thrown-off material is expected to be highly dispersed, and therefore not a threat to Earth. There is a chance that the ejected material may be broken into larger fragments, which could be very hazardous if they strike the Earth. This investigation will find the nuclear explosive surface charge required to perturb an asteroid out of an Earth-impact orbit. The size of the necessary charge calculated assumes that gravity limits ejecta production and that the asteroid is weak.[18]

The mass ejected per unit mass of explosive, when cratering is limited by gravity, is

$$\pi_v = \frac{\left\{0.16 - 0.24(d/a_e)\pi_2^{0.194} + 2.11\left[(d/a_e)\pi_2^{0.194}\right]^2 - 2.38\left[(d/a_e)\pi_2^{0.194}\right]^3 + 0.663\left[(d/a_e)\pi_2^{0.194}\right]^3\right\}}{\pi_2^{0.581}} \tag{23}$$

where d is the explosive burial depth and a_e is the equivalent TNT explosive mass radius. π_2 is the gravity scaling parameter.[18] The previous equation was obtained from MIT students, working on a project to deflect the asteroid Icarus from a fictitious Earth-collision trajectory. Their information was gathered from small-scale laboratory centrifuge experiments under high gravity and reduced pressure, and large-scale nuclear explosive tests. The students also performed a limited number of small-scale experiments conducted at reduced gravity and reduced atmospheric pressures.[19] The equation also assumes that the nuclear explosives can be assigned equivalent TNT mass based on their yield. π_2 is defined as

$$\pi_2 = \frac{\left(\frac{m}{\delta c}\right)^{1/3} g}{Q} \tag{24}$$

where m is the equivalent charge mass and δc is explosive charge density. Both the charge density and asteroid density are assumed to be 2Mg/m^3 for simplicity. Q is the energy per unit mass of TNT (4×10^6 J kg) and g is the asteroid surface gravity. The ejected material will only perturb the orbit of the NEO if it is thrown off at speeds exceeding the escape velocity.[18] The generalized equations of Housen *et al.* are used to calculate the mass of ejecta at speeds greater than escape velocity.[20]

$$\frac{m_e}{(\rho R_c^3)} = 0.32(2R / R_c)^{-0.61} \tag{25}$$

where R_c is the final crater radius in meters. Interpolating from data found in the NASA report implies that ~9.5, 1.5 x 10^3, and ~9.5 x 10^7 ktons of explosive energy are need to perturb the orbital velocity of 0.6, 1.5, and 6 km diameter NEOs by approximately 140 cm/sec. As previously stated, this is the amount of perturbation needed to move each NEO $20R_\oplus$ in 10 years. From these numbers it is obvious that at best, surface explosions are no better than radiative stand-off explosions, and the requirements are more uncertain.[18]

Fragmentation and dispersal

Studies done by Nakamura and Fujiwara on small-scale fragmentation experiments on solid rocks, demonstrate that the bulk of the fragments of a collisional disruption have velocities of approximately 10 m/sec.[21] The largest fragment of the NEO remaining, or the 'core', has a differential velocity of no more than ~1 m/sec. From equation 4, if the body is fragmented approximately 74 days before the Earth encounter, then most of the ≥ 10 m fragment will still strike the Earth. For small objects (less than 0.1 km), dispersal of the bulk of the fragments would not cause any hazards. Once the fragments become larger than 10 m, the Earth is posed for some harm. Large NEOs would have to be fragmented several orbits before intersection of with Earth to ensure that no danger is eminent.[14]

The debris cloud spreads along the orbit according to equation 6 and in the transverse direction according to equation 1. For characteristic ejecta velocity, 10 m/sec, the debris cloud would be approximately 10 $R_\oplus$ in radius (with some oscillation) and grow in length by about 200 $R_\oplus$ per orbit period. Instead of destroying the asteroid approximately74 days before impact, destroying it one orbit before impact reduces the percentage of debris encountered to 0.1%. However, if a large amount of fragments with $\Delta v \leq 1$ m/sec remained, as much of 10% of the mass could intercept Earth. Because of this uncertainty, it is better to intercept the NEO decades ahead of time in order to ensure the least amount of debris encounters Earth. Fragmentation is also a safe choice for small NEOs, whose fragments will cause no real harm.[14]

Ahrens *et al.* define catastrophic disruption of a NEO as fragmentation in which the largest fragment is ≤ ½ the mass of the original body. The energy density to accomplish this decreases with increasing size of body and becomes uncertain when extrapolated to bodies 1-10 km in size. For this investigation, however, the only interest is in the energy density necessary to break up an asteroid so that all fragments are ≤ 10 m in size. This leads to a higher energy density than that needed just to 'break in two'. They suggest that the energy density required is of the order of the energy density needed to 'break in two' a 10 m object, about $\sim 10^7$ erg/gram.[14]

Nuclear explosives are considered because of the large energy requirements to fracture a well-consolidated asteroid. The energy density will now be related to radius for a completely coupled (buried) nuclear charge. The empirical relations of Cooper are used for shock-induced particle velocity, v, against energy-scaled radius ($r/k\mathrm{T}^{1/3}$).[22] For dense, mainly igneous terrestrial rocks,

$$\log v = 5.233 - 2\log\left(\frac{r}{k\mathrm{T}^{1/3}}\right) \tag{26}$$

where Ahrens *et al.* state the r radius is hyrodynamically scaled by the one-third power of explosive yield (in kilotons TNT), $k\mathrm{T}^{1/3}$.[14] For soft rocks, the expression changes to

$$\log v = 4.590 - 2\log\left(\frac{r}{k\mathrm{T}^{1/3}}\right)$$

$$v = \frac{10^{4.59} kT^{2/3}}{r^2} \tag{27}$$

The shock-wave energy per unit mass is

$$E_{frac} = v^2(r, kT^{1/3}) \tag{28}$$

where v is found from either equation 26 or 26. Substituting equation 26 and 27 into equation 28 gives

$$r = \sqrt[4]{\left(\frac{10^{10.466} kT^{4/3}}{E_{frac}}\right)} \text{ for hard rock}$$

$$r = \sqrt[4]{\left(\frac{10^{9.18} kT^{4/3}}{E_{frac}}\right)} \text{ for soft rock} \tag{29}$$

for 1 kton, r is found to be 35 m. Thus, a 1 kton explosive charge is expected to fragment a 35-meter radius sphere of rock, if the charge is optimally placed. A 1 Mton explosive charge will create a 350 m-radius sphere of rock and 1 Gton explosive will create a 3500 m-radius sphere. These values are for soft rocks. In contrast, a 1 kton explosive will produce a 74-meter radius of fracture for a hard rock. This larger value is the result of the NEO being less attenuative.[14] Figure 6 gives the explosive charges necessary to move each NEO considering they are composed of soft or hard rock. For the NEOs presented in this paper, which will be considered soft rock, the explosive force necessary to produce 10^7 erg/g of energy is presented in Table 9 and is the result of manipulating equation 29 to get

$$kT = \left(\frac{r^2\sqrt{E_{frac}}}{10^{4.59}}\right)^{\frac{3}{2}} = \frac{r^3 E_{frac}^{3/4}}{10^{6.885}} \text{ Kton} \tag{30}$$

where r, the radius of the fragmented sphere, is equal to the radius of each NEO, E_{frac} is $\sim 10^7$ erg/g, and each NEO is considered to be soft rock.

Table 9. Explosive charge necessary to deliver 10^7 erg/g of energy to each NEO.

Object	Radius (km)	Explosive charge
1991 RB	0.3	~0.626 Mton
1991 VH	0.75	~9.78 Mton
3122 Florence	3.0	~626 Mton

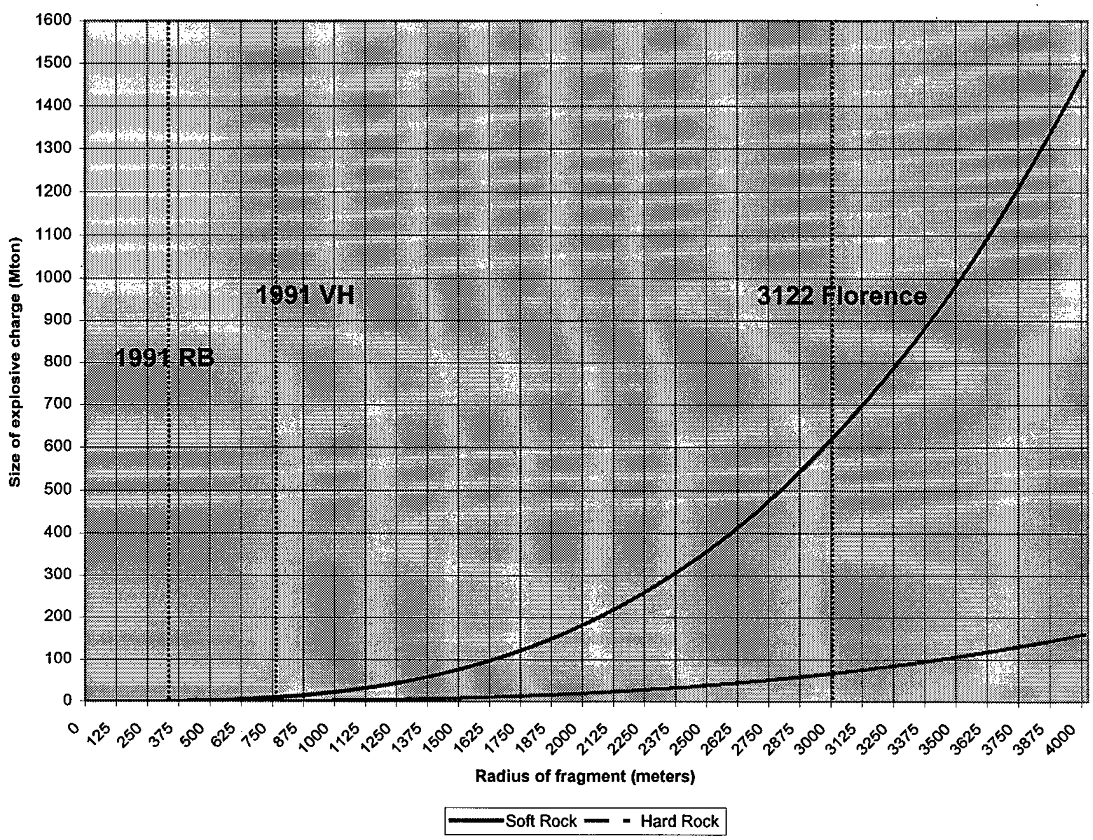


Fig 6. Nuclear charge needed to move each NEO in 10 years considering a composition of hard or soft rock.

The information listed in Table 9 assumes that the explosive is buried deep enough to produce optimum fragmentation. It is beneficial to have the nuclear device buried within the object since surface explosions transfer only a small fraction of their energy (0.2 to 1.8%) to the NEO. This energy is transferred in the form of radiative and hydrodynamic coupling. A much larger fraction of energy is transferred into the surrounding rock if the device is deeply buried.

Burial of nuclear charges to induce fragmentation and dispersal requires on-site drilling, which is difficult on a low-gravity object and may not be currently feasible.[14]

Perturbation by influence of a solar sail

The method of attaching a solar sail to a NEO is obviously going to be highly theoretical, but is included to give the investigation a well-rounded approach to NEO hazard mitigation. Even though it is not feasible now, the future has yet to be written. The solar sail is assumed to have a perfectly specular surface of large area. It is attached (somehow) to the NEO and the reflecting solar rays induce an acceleration to the NEO. Ivashkin and Smirnov give the relationship of the amount of distance perturbed using this method as

$$\delta l = 3\frac{\rho_O A}{m_{ast}} \cdot \left(\frac{a}{r_{ast}}\right)^2 \cdot \left[\cos^2 \vartheta \sin \vartheta\right] t_{ast}^2 \tag{31}$$

where ρ_o is the normal solar radiation pressure at the Earth orbit, a is the mean radius of this orbit (semi-major axis) in meters, A is the solar sail area, ϑ is the angle between the direction from the Sun to the asteroid and the normal to the sail surface, and t_{ast} is the time of the sail influence on the asteroid motion in seconds.[15] The radius of the asteroid's orbit, r_{ast}, is taken to be the value of the semi-major axis for simplification of the calculations. It is accepted that A = 4 x 10^5 m^2 (which approximately corresponds to the possibility of modern technology). In Figure 7 we find the optimum angle for ϑ by plotting the values of $\left[\cos^2 \vartheta \sin \vartheta\right]$ over one full rotation and finding the maximum.

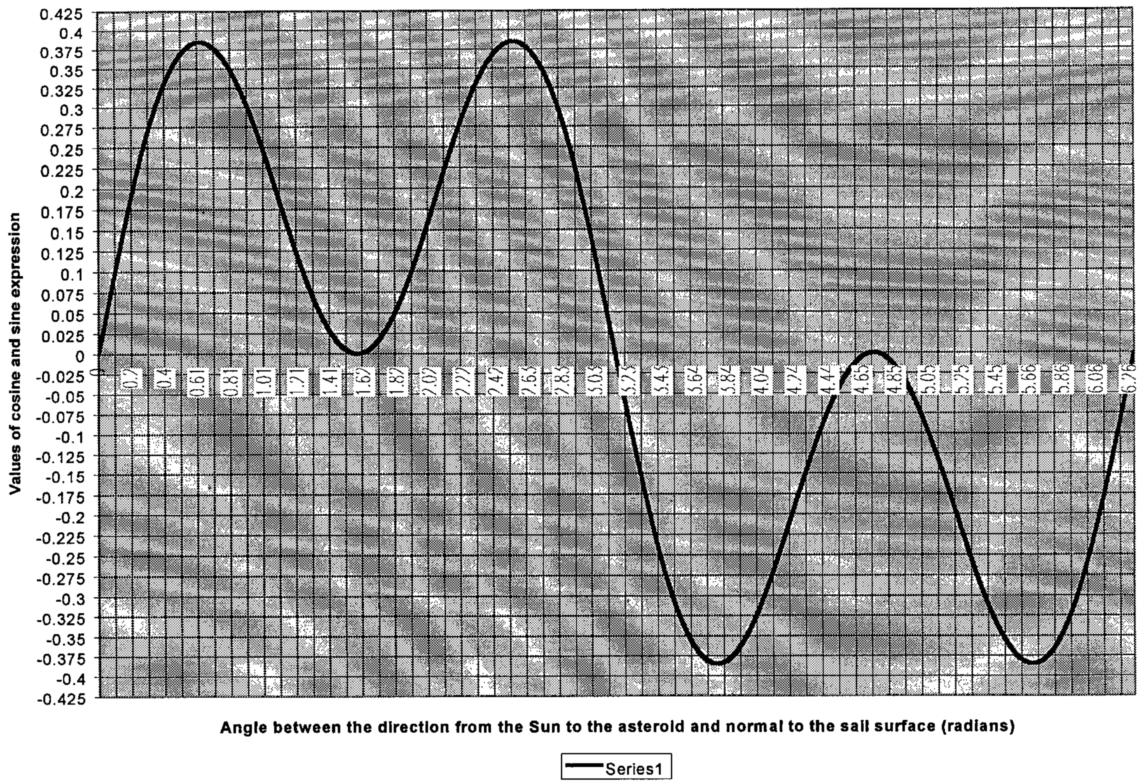


Fig 7. Plot of $\left[\cos^2 \vartheta \sin \vartheta\right]$ over 2π.

Using Figure 7, shows that the optimal angle to set the solar sail is 35.266°. Using this value for ϑ returns the maximum value for the cosine and sine expression (~0.3849). The next step is to solve for t_{ast} to find the time it takes to move the NEO δl=20 $R_{\oplus}$ where

$$t_{ast} = \sqrt{\left(\frac{m_{ast}\delta l}{3\rho_O A(r_E / r_{ast})^2 (0.3849)}\right)} \text{ seconds} \tag{32}$$

Figure 8 shows the amount of time needed to perturb each NEO by 20 $R_{\oplus}$. In this case, t_{ast} is basically dependent upon two variable, r_{ast} and m_{ast}. Each line corresponds to a different r_{ast}, and hence one of the three NEO's presented in this paper. The corresponding time, t_{ast}, is listed for each NEO. As shown in the graph, using a solar sail to change a NEO's orbit seems feasible for diameters ≈≤ 1.7 km. For diameters larger than that value, it takes more than 25 years to move the NEO out of Earth's way. Using a solar sail has the advantage of not needing any fuel to operate. Unfortunately, the practicality of this method is not currently achievable.

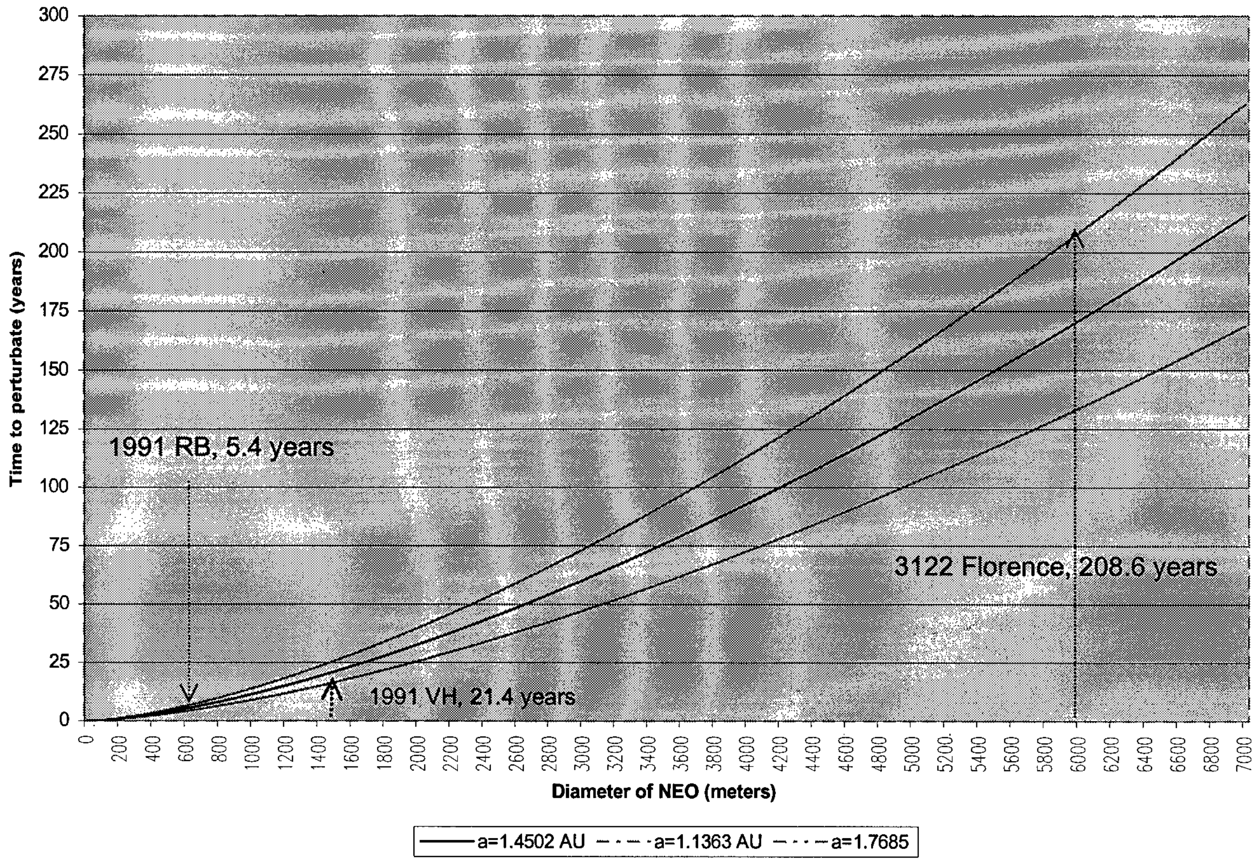


Fig 8. Time need to perturb each NEO's orbit using a solar sail.

<u>"Painting" of the asteroid surface</u>

This method will pertain just to asteroids because of the infeasibility of interacting with an comet travelling at speeds of up to 60 km/sec. Fortunately, all three of the NEOs presented in this paper are asteroids, so an analysis may be done. Here one assumes the ability to change the capacity of an asteroid surface to reflect solar radiation. Ivashkin and Smirnov report that by "painting" an asteroid surface, the orbit will change in a necessary way in accordance to the Newton-Lebedev law.[15] This effect can be achieved by painting the asteroid surface or covering the asteroid with a thin specular film to change the reflecting capacity of the asteroid surface.

It is assumed that before the asteroid's surface is "painted", solar radiation pressure had no effect on the NEO. The presumption is that after the asteroid is "painted", the surface becomes perfectly specular. The following expression gives the perturbing acceleration that applies to the asteroid where its surface is a sphere with a radius $R_{ast.}$[15]

$$\Delta v' = \frac{\pi R_{ast}^2}{m_{ast}} p_O \left(\frac{r_\oplus}{r_{ast}} \right)^2 \tag{33}$$

This perturbing acceleration is directed radially from the Sun. The displacement, δl, that results is

$$\delta l = 4\pi n \left(\frac{r_{ast}}{\mu_{sun}} \right) \cdot \left[\frac{\pi R_{ast}^2}{m_{ast}} p_O r_\oplus^2 \right] = nT^2 \left[\frac{R_{ast}^2}{m_{ast}} p_O \left(\frac{r_\oplus}{r_{ast}} \right)^2 \right] \tag{34}$$

where once again, T is the orbital period. To find the time needed to move the NEO 20 $R_\oplus$, we solve for n and multiply it by T.

$$n = INT \left| \frac{m_{sat} \delta l}{T^2 p_O R_{ast}^2 (r_\oplus / r_{ast})^2} \right| \tag{35}$$

Table 10. The characteristics of the controlled change of each NEO's orbit by "painting" the asteroid.

Object	Radius (km)	Semi-major axis (AU)	Revolutions n	Time nT (years)
1991 RB	0.3	1.4502	50	86.02
1991 VH	0.75	1.1363	158	190.34
3122 Florence	3.0	1.7685	403	949.91

The method of "painting" an asteroid may not be too difficult to realize, but is less effective than other methods.

Discussion of Applications

In this section, we will do a comparative analysis of the methods presented in the previous section. The goal is to recommend a method of asteroid hazard mitigation for each of the three NEO's. If a real threat of impact was imminent, further study should be done on each of the recommended approaches to further define the necessary requirements. The approach of this section is to look at each NEO one at a time and present conclusions.

1991 RB

Since 1991 RB is relatively small (compared to the others) asteroid there are more options available to perturb it's orbit out of an Earth-impact trajectory. The amount of time needed to perturb the NEO by 20 $R_\oplus$ through a variety of methods is presented below in Table 11. The other techniques have certain requirements, either size of nuclear explosion or amount of mass to be ejected, to perturb the NEO in a certain amount of time. These requirements and time parameters are listed in Table 12.

Table 11. Amount of time needed to perturb 1991 RB by 20 $R_\oplus$.

Impact w/ a ~200 ton spacecraft	Attaching a 4 x 10^5 m^2 solar sail to 1991 RB	"Painting" the surface of 1991 RB
244.28 years	5.4 years	86.02 years.

Table 12. Requirements needed to move 1991 RB by 20 $R_\oplus$ by use of other method techniques.

Method of hazard mitigation	Time requirement	Resulting requirements
Deflection by Mass driver	30 years	3.45 x 10^7 kg of mass ejected
Deflection by nuclear explosion radiation	10 years	~9.3 kton
Fragmentation and dispersal	10 years	~626 kton

My decision of the recommended approach to move 1991 RB would be based primarily by how much lead-time there is until impact. Therefore, I have two recommendations of methods to move 1991 RB out of an Earth-impact trajectory based upon time until impact. The first is based upon having a long lead-time (≈250 years) until impact. This situation could occur if astronomers perform accurate, long-term, orbit propagation analysis and find that 1991 RB would eventually collide with Earth. If this is the case, I recommend moving the NEO's orbit by impacting it with a large spacecraft. This method avoids the politics of having a nuclear weapon in space and the complicated logistics of interacting with the NEO. By interacting, I imply the problem of attaching a solar sail, "painting" the surface, and using a mass driver. Of course the problem of launching such a large spacecraft into an NEO-impact trajectory must be overcome. If there was a short time until impact, i.e. greater than15 years, I recommend deflection by nuclear explosion radiation. This method requires a relatively small nuclear charge and the only main obstacle is detonating the device at the optimum height above the asteroid. Of course, this means putting a nuclear weapon into space. My insight leads me to believe that considering the urgency and possible consequences, the public would understand the necessity of launching the device into space.

1991 VH

The larger diameter of 1991 VH (1.5 km) makes many methods of hazard mitigation not viable. Tables 13 and 14 summarize the results of the previous mitigation analysis for 1991 VH.

Table 13. Amount of time needed to perturb 1991 VH by 20 $R_\oplus$ using a variety of methods.

Impact w/ a ~200 ton spacecraft	**Attaching a 4×10^5 m^2 solar sail to 1991 VH**	**"Painting" the surface of 1991 VH**
21,161 years	21.4 years	190.34 years

Table 14. Requirements needed to move 1991 VH by 20 $R_\oplus$ by use of other method techniques.

Method of hazard mitigation	Time requirement	Resulting requirements
Deflection by Mass driver	30 years	5.537×10^8 kg of mass ejected
Deflecton by nuclear explosion radiation	10 years	~1.47 Mton
Fragmentation and dispersal	10 years	~9.78 Mton

Long lead times of warning prompt me to recommend "painting" the surface of 1991 VH. This may not be currently feasible, but shows great promise if more research is done in this area. This method involves the problem of covering the entire asteroid with a reflective material, but it is a passive system that needs no control after applied. If there was only a short time of warning before impact, deflection by nuclear radiation seems the best choice. It requires a relatively small detonation, which could be increased if there was less than 10 years until impact. This method requires less detailed knowledge of the physical characteristics of the NEO. In addition, the size of the nuclear charge required is technologically feasible.

<u>3122 Florence</u>

This NEO presents special challenges in determining what method to use in order to move it out of an Earth-impact trajectory because of its large size. It is a serious matter as well, because of the extreme consequences of it impacting Earth. The end of our existence is virtually guaranteed.[2] The number of methods that can be used to move the NEO's orbit are greatly reduced. Tables 15 and 16 illustrate this point.

Table 15. Amount of time needed to perturb 3122 Florence by 20 $R_\oplus$ using a variety of methods.

Impact w/ a ~200 ton spacecraft	Attaching a 4×10^5 m^2 solar sail to 1991 VH	"Painting" the surface of 1991 VH
251,161 years	208.6	949.91

Table 16. Requirements needed to move 3122 Florence by 20 $R_{\oplus}$ by use of other method techniques.

Method of hazard mitigation	Time requirement	Resulting requirements
Deflection by Mass driver	30 years	5.537×10^8 kg of mass ejected
Deflecton by nuclear explosion radiation	10 years	~93.3 Mton
Fragmentation and dispersal	10 years	~626 Mton

For long lead-times, using a solar sail shows good results. If the feasibility of this method is beyond the means of technology at the time of prediction, nuclear explosion radiation is the only other alternative. Short lead-times lead to the conclusion of using nuclear explosion radiation as well.

Currently, more research of the suggested methods may be warranted, but actual engineering of systems is probably not necessary. The high cost of such an activity is not justified with such a low probability of hazardous impact. Technology changes at such a rapid pace that designing a system until a threat is determined is the most likely course of action to follow.

Conclusion

In 1991, NASA conducted a series of studies of the asteroid-impact threat to Earth and ways in which to avoid it. These studies were performed at the behest of the US House of Representatives.[15] The recent *Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop* report quantified the hazards of Earth impactors and its results were presented in the introduction of this investigation. The Spaceguard Survey proposed at that workshop is a program that in 20 years could inventory almost all of the potentially threatening asteroids large enough to precipitate a global catastrophe. It would also give a lead-time of several months for most incoming comets. The Survey would cost approximately ~$50 million for construction and start up costs, and $10 million for annual operating expenses. It would be able to catalog most large objects to all the way down to the size of NEOs that would disintegrate in the atmosphere. The workshop proposed that there would be warning lead-times of decades for asteroids. For long period comets, like those similar to the Swift-Tuttle comet, warning of an impact may only be a few months.[23]

Experts predict that the most likely result of the Spaceguard Survey would be to find no objects larger than 1 km in immediately threatening orbits. It would also be able to find all other NEO of any size that are predicted to strike Earth within the next century or so. If an object was found to have an orbit that will strike Earth, action can be taken to mitigate the hazard. Even if a warning is too short to mitigate, people near possible impact sites can be evacuated.[2]

Earth has always been threatened by the possibility of an impact from a NEO, but it has only been recently that mankind has realized how possible impacts could effect our civilization. The probability of an impact having severe consequences on modern life is low, but it is not zero. Chapman and Morrison in their article, "*Impacts on the Earth by asteroids and comets: assessing the hazard*" consider the hazard threat in the following excerpt.

> "Society must address the public policy issues raised by the impact hazard and proposals to deal with it. Assuming, as we do, that it is appropriate to tamper with a natural process that may have shaped evolution of life on our planet, there are questions of strategy. For example, in the case of asteroids, a comprehensive sky survey would likely provide decades or more warning, permitting decisions about specific deflection schemes to be deferred until they really are required. But a large comet might be identified on an impact trajectory with a lead time of only a few months; should we prepare in advance to deal – at great expense – with such a contingency, because of its 'unacceptable' consequences, even though it is extremely unlikely?"[2]

Man has the capability to catalog most of the NEO's that may be potentially threatening to Earth, but only a small percentage of them have been discovered to date. If the Spaceguard Survey was put into place and discovered that the Earth was in no immediate threat, we would know that we were safe from harm; safe at least from the asteroid threat. It has been estimated that even if the survey did little to address the hazard posed by long-period comets, it would reduce the known hazard by at least a factor of three. However, if the survey did find a NEO on an impact trajectory within the next few decades, this investigation shows that mitigation of the threat is possible. Therefore, spending the money to get a complete survey can be justified.[2]

They continue their discussion with the ensuing remarks.

> "There may be a much more serious indirect threat from small impacts: misidentification of an asteroid airburst could trigger an inappropriate military response from a nuclear power in times of tension. High-altitude airbursts with the energy of the Hiroshima bomb occur annually. It is important that such natural phenomena be understood, especially by the military decision-makers of nations with nuclear capability. This may be the most important immediate issue raised by recognition of the impact hazard."[2]

Building an actual mitigation system has been proposed by Alekseev *et al.*[24] They suggest a Space Rocket Interception Complex (SRIC). It is an interception complex consisting of a space interceptor with a nuclear explosive device, a booster, a launch-vehicle and supporting systems. They also discuss that the SRIC be developed by an international community in case of a threat. Figure 9 is an illustration of the SRIC.

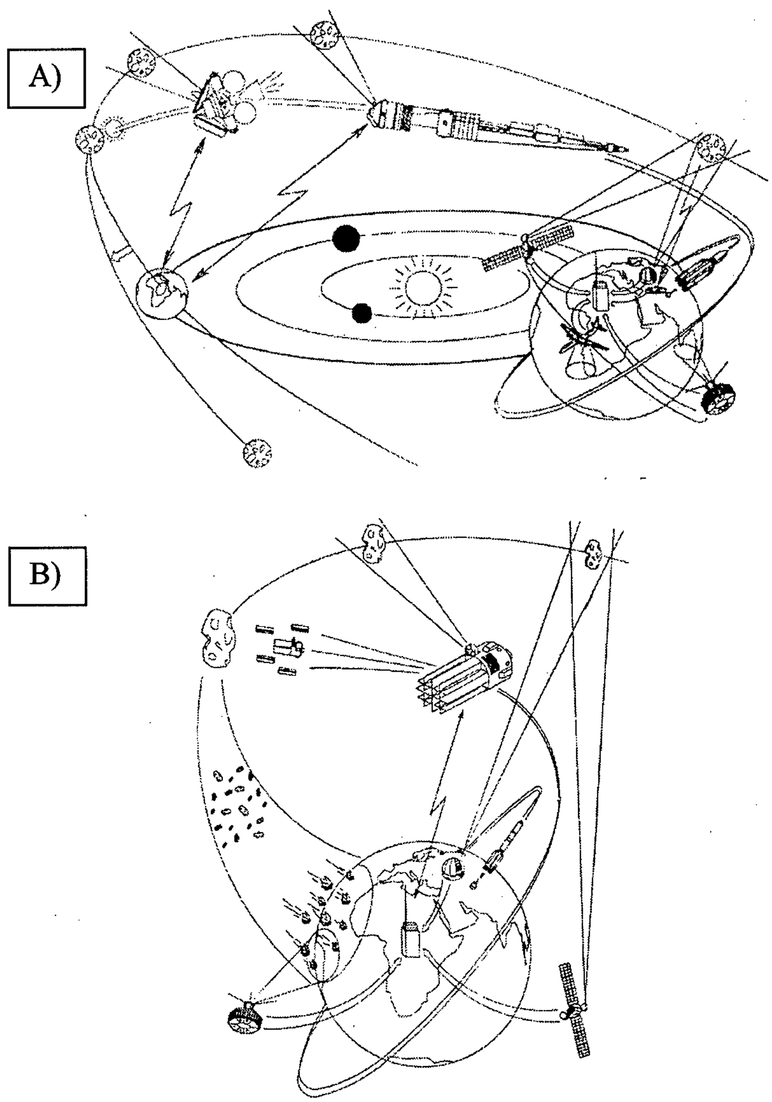


Fig 9. A) Function scheme of the Earth Protection System. B) Function scheme of operative interceptor with impact penetrators.[25]

Another step in being able to deal with the NEO threat is the ability to rendezvous with one. In an effort to accomplish this, the spacecraft Clementine I was launched in January 1994 with the mission of going to the moon to map its surface and performing a close flyby of the near Earth asteroid Geographos. Clementine I successfully mapped 100% of the Moon's surface, but due to a software bug, it lost its attitude control fuel during the transfer phase from the lunar orbit to the Geographos transfer trajectory. [25]

In the summer of 1995, the Clementine program office, now at the USAF/Phillips Laboratory, made the decision for a follow-on Clementine II mission. The primary mission of Clementine II is to perform a close, fast flyby of multiple near Earth asteroid, launch science probes which will impact the asteroids, and to image the actual impact. The objectives of the mission are to perform a cost-effective demonstration of lightweight spacecraft and sensor technologies, to test autonomous navigation and terminal optical navigation techniques for encounter of cold bodies, and to demonstrate the feasibiltiy for quick-reaction observation of near-Earth objects. The cost of the project was estimated to be $30 million.[25]

The Clementine II mission was line-item vetoed by President Clinton in October of 1997. The mission was vetoed because the administration was concerned the project would violate the Antiballistic Missile Treaty which prohibits launching weapons into space. An article that appeared in *Time Magazine* that discusses the cancellation of the project appears in the appendix of this investigation.[26]

As public recognition of the impact hazard grows, due to frequent discoveries and reports of 'near misses', movies of NEO impacts coming out shortly, and many books [27],[28] written about the subject, questions about the impact hazard will continue to fuel public debate. The impact hazard must be weighed against the debates over society's priorities in dealing with other potential ecological disasters and hazards in general. This is to ensure that proper time, attention, and resources are addressed to all potential hazards to society.

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Appendix

Catalogue of Near Earth Asteroids: orbits of known Atens/Apollos/Amors as of 1995 March 21. Semimajor axes (a) are in astronomical units, angles are in degrees, and estimated diameters are in kilometers. The final column gives the spectral type if available. Data supplied by David Tholen of the University of Hawaii.

TABLE 1: ATENS

	Desig	a	e	i	Node	Peri	M	Epoch	Diam	Type
2062 Aten	1976 AA	0.9666	0.1826	18.93	107.99	147.82	299.11	2449800.5	1	S
2100 Ra-Shalom	1978 RA	0.8320	0.4365	15.75	170.24	355.95	104.33	2449800.5	4	C
2340 Hathor	1976 UA	0.8438	0.4499	5.85	210.93	39.83	3.31	2449800.5	0.5	CSU
3362 Khufu	1984 QA	0.9894	0.4686	9.91	151.97	54.84	345.56	2449800.5	1	
3554 Amun	1986 EB	0.9737	0.2804	23.35	358.01	359.34	308.42	2449800.5	3	
3753	1986 TO	0.9977	0.5147	19.81	125.70	43.62	67.79	2449800.5	5	
5381 Sekhmet	1991 JY	0.9474	0.2959	48.97	57.88	37.41	177.08	2449800.5	2	
5590	1990 VA	0.9853	0.2793	14.19	215.72	34.35	305.83	2449800.5	0.4	
5604	1992 FE	0.9270	0.4054	4.78	311.43	82.36	234.57	2449800.5	2	
	1995 CR	0.9057	0.8678	4.00	342.33	322.10	345.03	2449800.5	0.2	
	1994 XL1	0.6708	0.5263	28.19	252.02	356.49	27.61	2449800.5	0.3	
	1994 WR12	0.7540	0.4053	7.06	62.41	205.59	305.39	2449800.5	0.2	
	1994 TF2	0.9932	0.2836	23.75	174.64	349.62	29.72	2449800.5	0.6	
	1994 GL	0.6844	0.5019	3.64	196.46	179.06	69.10	2449800.5	0.06	
	1993 VD	0.8766	0.5493	2.05	2.25	253.51	348.33	2449800.5	0.2	
	1993 DA	0.9353	0.0937	12.40	328.53	353.96	300.17	2449800.5	0.02	
	1992 BF	0.9079	0.2710	7.25	314.94	336.28	82.03	2449800.5	0.6	
	1991 VE	0.8905	0.6638	7.20	61.49	193.33	93.67	2449800.5	0.6	
	1989 VA	0.7286	0.5947	28.79	224.95	2.79	42.66	2449800.5	1	
	1989 UQ	0.9152	0.2649	1.28	178.03	14.62	272.91	2449800.5	0.6	
	1954 XA	0.7775	0.3451	3.91	188.77	58.73	120.76	2449800.5	0.6	

TABLE 2: APOLLOS

	Desig	a	e	i	Node	Peri	M	Epoch	Diam	Type
1566 Icarus	1949 MA	1.0780	0.8267	22.88	87.47	31.20	10.06	2449800.5	2	
1620 Geographos	1951 RA	1.2455	0.3354	13.33	336.65	276.74	191.54	2449800.5	2.3	S
1685 Toro	1948 OA	1.3670	0.4360	9.37	273.70	126.95	18.24	2449800.5	12	S
1862 Apollo	1932 HA	1.4711	0.5598	6.35	35.27	285.58	44.34	2449800.5	1.5	Q
1863 Antinous	1948 EA	2.2600	0.6062	18.41	346.84	266.91	280.57	2449800.5	2	SU
1864 Daedalus	1971 FA	1.4609	0.6146	22.17	6.09	325.43	126.42	2449800.5	3	SQ
1865 Cerberus	1971 UA	1.0801	0.4669	16.09	212.35	325.13	204.71	2449800.5	1	S
1866 Sisyphus	1972 XA	1.8933	0.5391	41.16	63.01	292.97	224.27	2449800.5	9.6	
1981 Midas	1973 EA	1.7761	0.6500	39.83	356.48	267.68	81.87	2449800.5	4	
2063 Bacchus	1977 HB	1.0779	0.3495	9.41	32.63	55.05	92.76	2449800.5	2	
2101 Adonis	1936 CA	1.8738	0.7648	1.34	350.02	42.30	42.70	2449800.5	0.7	
2102 Tantalus	1975 YA	1.2901	0.2985	64.01	93.70	61.60	13.25	2449800.5	3.3	
2135 Aristaeus	1977 HA	1.5997	0.5031	23.04	190.74	290.63	341.09	2449800.5	1	
2201 Oljato	1947 XC	2.1759	0.7106	2.51	76.34	95.81	254.33	2449800.5	2	
2212 Hephaistos	1978 SB	2.1681	0.8335	11.77	27.75	208.36	82.17	2449800.5	5	SG
2329 Orthos	1976 WA	2.4024	0.6587	24.41	168.84	145.75	352.75	2449800.5	4	
3103 Eger	1982 BB	1.4060	0.3546	20.93	129.22	253.79	31.51	2449800.5	3	
3200 Phaethon	1983 TB	1.2713	0.8901	22.10	264.87	321.83	23.14	2449800.5	5.2	F
3360	1981 VA	2.4645	0.7430	21.74	244.81	60.58	183.33	2449800.5	2	
3361 Orpheus	1982 HR	1.2091	0.3225	2.68	189.11	301.53	303.54	2449800.5	0.6	
3671 Dionysus	1984 KD	2.1952	0.5429	13.62	81.76	203.63	105.31	2449800.5	2	
3752 Camillo	1985 PA	1.4136	0.3023	55.54	147.33	312.21	154.91	2449800.5	3	
3757	1982 XB	1.8350	0.4465	3.87	74.50	16.77	331.11	2449800.5	0.5	S
3838 Epona	1986 WA	1.5047	0.7018	29.28	235.06	49.43	219.51	2449800.5	3	
4015 Wilson-Harrington	1979 VA	2.6418	0.6219	2.78	270.14	91.07	216.92	2449800.5	4	CF
4034	1986 PA	1.0599	0.4441	11.17	157.44	296.44	222.07	2449800.5	1	
4179 Toutatis	1989 AC	2.5154	0.6361	0.47	128.30	274.08	212.59	2449800.5	3.3	
4183 Cuno	1959 LM	1.9809	0.6369	6.76	295.17	235.22	321.88	2449800.5	5	
4197	1982 TA	2.2972	0.7727	12.20	9.50	119.23	182.29	2449800.5	5	
4257 Ubasti	1987 QA	1.6471	0.4684	40.70	168.65	278.89	165.20	2449800.5	2	
4341 Poseidon	1987 KF	1.8357	0.6787	11.86	107.55	15.47	83.01	2449800.5	3	
4450 Pan	1987 SY	1.4418	0.5865	5.51	311.52	291.38	165.58	2449800.5	1.5	
4486 Mithra	1987 SB	2.2012	0.6626	3.04	81.94	168.47	138.47	2449800.5	3	
4544 Xanthus	1989 FB	1.0420	0.2502	14.14	23.44	333.62	66.04	2449800.5	1.5	
4581 Asclepius	1989 FC	1.0226	0.3571	4.91	179.85	255.00	354.62	2449800.5	0.3	
4660 Nereus	1982 DB	1.4897	0.3602	1.41	313.97	157.96	91.02	2449800.5	0.8	
4769 Castalia	1989 PB	1.0631	0.4832	8.88	325.04	121.22	334.57	2449800.5	1.6	
4953	1990 MU	1.6208	0.6569	24.42	77.42	77.38	167.94	2449800.5	5	
5011 Ptah	6743 P-L	1.6350	0.4999	7.39	10.38	105.36	124.94	2449800.5	1.5	
5131	1990 BG	1.4866	0.5700	36.38	109.83	135.69	242.65	2449800.5	6	
5143 Heracles	1991 VL	1.8338	0.7713	9.18	310.04	226.39	78.41	2449800.5	6	
5189	1990 UQ	1.5508	0.4778	3.58	134.80	159.37	148.71	2449800.5	1	
5496	1973 NA	2.4337	0.6382	68.02	100.38	118.24	272.29	2449800.5	4	
5645	1990 SP	1.3548	0.3874	13.51	45.23	47.96	255.08	2449800.5	2	
5660	1974 MA	1.7861	0.7628	37.94	301.85	126.71	216.91	2449800.5	3	
5693	1993 EA	1.2721	0.5853	5.05	96.60	258.56	336.98	2449800.5	1.5	
5731	1988 VP4	2.2632	0.6526	11.64	282.06	215.63	283.48	2449800.5	3	
5786 Talos	1991 RC	1.0814	0.8267	23.24	160.67	8.26	173.14	2449800.5	2	
5828	1991 AM	1.6977	0.6957	30.04	124.91	152.53	285.71	2449800.5	2	
6037	1988 EG	1.2690	0.4994	3.48	182.27	241.46	18.74	2449800.5	0.7	
6047	1991 TB1	1.4537	0.3521	23.46	5.57	103.55	292.54	2449800.5	1.5	
6053	1993 BW3	2.1474	0.5288	21.59	317.96	74.57	298.72	2449800.5	5	
6063	1984 KB	2.2157	0.7643	4.85	169.25	336.49	113.98	2449800.5	4	
6239	1989 QF	1.1513	0.4127	3.93	344.15	239.50	250.24	2449800.5	0.9	
	1995 EK1	2.2509	0.7746	8.81	355.03	296.53	342.08	2449800.5	1	
	1995 DW1	1.0405	0.4380	15.10	348.26	326.88	265.09	2449800.5	0.2	
	1995 DV1	3.1257	0.6915	3.69	171.63	283.97	14.05	2449800.5	0.07	
	1995 CS	1.9400	0.7753	2.61	135.06	252.05	34.39	2449800.5	0.04	
	1995 BL2	1.2315	0.4943	23.08	311.72	348.22	252.60	2449800.5	1	
	1994 XM1	2.0884	0.5688	4.11	76.35	40.66	24.37	2449800.5	0.01	
	1994 XG	1.5719	0.4900	11.32	231.10	46.14	157.53	2449800.5	1	
	1994 XD	2.3590	0.7291	4.34	96.96	247.73	48.66	2449800.5	0.6	
	1994 VH8	1.6355	0.4428	3.37	37.78	314.14	84.29	2449800.5	0.01	
	1994 UG	1.2258	0.2457	4.49	11.73	225.91	247.95	2449800.5	0.2	
	1994 RC	2.2678	0.6018	4.72	345.45	284.34	75.84	2449800.5	0.6	
	1994 RB	2.4883	0.6394	26.62	338.94	52.47	41.21	2449800.5	0.1	
	1994 PC1	1.3457	0.3277	33.50	117.29	47.53	273.04	2449800.5	2	
	1994 PM	1.4775	0.7523	17.94	139.38	303.27	92.69	2449800.5	1	

1994	NE	2.0360	0.6045	27.53	104.29	246.20	72.70	2449800.5	0.4
1994	LX	1.2614	0.3464	36.90	110.65	349.01	24.35	2449800.5	4
1994	GV	2.0300	0.5228	0.45	19.31	154.30	125.40	2449800.5	0.01
1994	GK	1.9609	0.6064	5.66	14.67	111.58	142.34	2449800.5	0.06
1994	FA	1.7358	0.4157	13.04	355.09	154.66	170.31	2449800.5	0.04
1994	ES1	1.4117	0.5897	0.94	352.34	279.11	188.61	2449800.5	0.008
1994	EU	1.3725	0.2749	6.44	350.96	145.77	250.26	2449800.5	0.03
1994	EK	1.9992	0.6067	5.76	333.54	98.01	159.90	2449800.5	0.4
1994	CN2	1.5732	0.3949	1.43	98.93	247.89	345.40	2449800.5	2
1994	CK1	1.8977	0.6200	4.40	328.11	27.67	247.78	2449800.5	1.5
1994	CJ1	1.4908	0.3258	2.31	171.61	64.92	161.22	2449800.5	0.2
1994	CC	1.6370	0.4169	4.63	268.11	24.63	63.62	2449800.5	1
1994	CB	1.1491	0.1450	18.25	310.04	288.40	242.82	2449800.5	0.2
1994	AH2	2.5255	0.7114	9.63	163.68	24.82	80.74	2449800.5	2
1993	XN2	2.1173	0.5356	25.38	59.06	312.89	172.33	2449800.5	2
1993	WD	1.0066	0.2666	63.46	55.89	132.30	10.01	2449800.5	2
1993	VW	1.6949	0.4843	8.68	230.58	280.93	174.42	2449800.5	2
1993	VB	1.9098	0.5197	5.06	145.23	322.63	164.63	2449800.5	0.5
1993	VA	1.3559	0.3912	7.26	132.60	336.35	281.97	2449800.5	1.5
1993	UC	2.4380	0.6626	25.99	165.41	322.95	103.06	2449800.5	3
1993	UA	2.0201	0.5244	4.58	26.48	330.11	186.57	2449800.5	0.04
1993	TZ	2.0235	0.5633	4.16	202.96	231.23	166.07	2449800.5	0.02
1993	QA	1.4767	0.3161	12.63	146.09	323.25	198.77	2449800.5	1
1993	PC	1.1543	0.4743	4.15	336.85	168.12	289.61	2449800.5	1
1993	PB	1.4232	0.6064	40.84	315.32	212.21	79.63	2449800.5	2
1993	KA2	2.2273	0.7745	3.18	238.78	261.44	213.05	2449800.5	0.006
1993	KH	1.2338	0.3110	12.80	53.86	293.57	46.54	2449800.5	0.6
1993	KA	1.2552	0.1974	6.05	235.17	341.90	125.65	2449800.5	0.02
1993	HP1	1.9915	0.5104	8.00	36.37	152.25	251.92	2449800.5	0.02
1993	HD	1.4322	0.6633	5.74	201.77	252.55	78.03	2449800.5	0.1
1993	HC	1.9888	0.5069	9.39	200.85	306.32	266.26	2449800.5	0.3
1993	GD	1.1022	0.2380	15.45	200.87	201.92	24.57	2449800.5	0.3
1993	FA1	1.4262	0.2886	20.46	186.67	343.60	68.99	2449800.5	0.03
1993	BX3	1.3953	0.2809	2.79	174.99	289.77	123.00	2449800.5	0.3
1993	BW2	1.3352	0.3061	21.91	120.50	287.37	185.43	2449800.5	1
1992	YD3	1.1661	0.1372	27.04	273.63	173.75	284.16	2449800.5	0.02
1992	UY4	2.6543	0.6198	2.83	308.41	37.43	211.13	2449800.5	1
1992	TB	1.3418	0.4622	28.31	185.02	5.92	5.91	2449800.5	1
1992	SY	2.2087	0.5503	8.02	5.62	114.98	221.63	2449800.5	1
1992	SK	1.2485	0.3249	15.31	8.36	233.48	14.91	2449800.5	1
1992	QN	1.1908	0.3593	9.58	355.40	202.11	92.97	2449800.5	2
1992	LC	2.5193	0.7049	17.84	61.28	89.64	267.31	2449800.5	4
1992	JD	1.0347	0.0316	13.54	221.92	285.87	338.93	2449800.5	0.03
1992	JB	1.5564	0.3598	16.07	217.81	306.75	203.71	2449800.5	1
1992	HF	1.3907	0.5617	13.30	212.91	128.05	219.90	2449800.5	0.3
1992	HE	2.2402	0.5722	37.36	26.62	262.57	295.62	2449800.5	6
1992	DU	1.1598	0.1748	25.05	337.28	121.63	207.37	2449800.5	0.04
1992	CC1	1.3914	0.3749	36.88	348.61	21.90	70.72	2449800.5	4
1992	BC	1.4135	0.3484	14.21	122.82	77.07	277.34	2449800.5	0.6
1991	XA	2.2690	0.5704	5.28	76.17	309.11	357.59	2449800.5	0.06
1991	WA	1.5752	0.6425	39.65	66.07	241.73	275.36	2449800.5	2
1991	VK	1.8436	0.5059	5.41	294.37	173.25	101.30	2449800.5	1.5
1991	VH	1.1363	0.1437	13.91	138.82	206.99	320.12	2449800.5	1.5
1991	VG	1.0269	0.0491	1.44	73.51	24.15	38.74	2449800.5	0.007
1991	VA	1.4288	0.3516	6.52	36.97	313.41	17.16	2449800.5	0.02
1991	TF3	2.0414	0.5303	14.04	6.02	303.20	86.12	2449800.5	0.6
1991	TB2	2.3977	0.8352	8.62	296.41	195.66	317.29	2449800.5	1.5
1991	TU	1.4068	0.3306	7.55	192.73	222.09	5.56	2449800.5	0.008
1991	TT	1.1929	0.1605	14.75	191.77	218.11	209.31	2449800.5	0.02
1991	RB	1.4502	0.4839	19.53	358.88	68.71	333.61	2449800.5	0.6
1991	LH	1.3520	0.7305	52.06	280.16	203.92	253.90	2449800.5	1.5
1991	JX	2.5190	0.5990	2.31	212.16	64.47	337.11	2449800.5	0.8
1991	JW	1.0383	0.1183	8.71	53.41	301.76	116.55	2449800.5	0.5
1991	GO	1.9594	0.6618	9.66	24.30	88.58	177.46	2449800.5	0.6
1991	EE	2.2460	0.6244	9.76	168.46	115.03	30.78	2449800.5	1
1991	DG	1.4271	0.3629	11.15	179.63	63.05	89.94	2449800.5	0.6
1991	CB1	1.6870	0.5946	14.56	316.85	345.53	191.78	2449800.5	1
1991	CS	1.1229	0.1646	37.10	156.23	249.26	235.76	2449800.5	1
1991	BN	1.4426	0.3979	3.44	268.46	80.54	237.31	2449800.5	0.4
1991	BB	1.1863	0.2725	38.47	294.34	322.81	333.44	2449800.5	2
1991	BA	2.1652	0.6734	2.12	118.25	71.86	98.58	2449800.5	0.008

	1991 AQ	2.2210	0.7771	3.21	342.06	239.69	78.62	2449800.5	1.5	
	1990 UO	1.2341	0.7582	29.34	205.06	332.95	7.23	2449800.5	0.3	
	1990 UN	1.7093	0.5277	3.66	7.62	97.08	325.95	2449800.5	0.08	
	1990 UA	1.7212	0.5519	0.96	102.09	203.87	9.71	2449800.5	0.5	
	1990 TG1	2.4849	0.6929	9.06	204.37	33.28	114.25	2449800.5	4	
	1990 SS	1.7029	0.4748	19.39	359.43	115.74	310.26	2449800.5	0.6	
	1990 SM	2.1567	0.7754	11.56	137.28	105.91	168.03	2449800.5	2	
	1990 OS	1.6691	0.4590	1.10	347.40	20.03	33.69	2449800.5	0.4	
	1990 MF	1.7468	0.4556	1.86	209.87	113.89	0.37	2449800.5	0.8	
	1990 HA	2.5777	0.6932	3.88	184.43	307.89	80.94	2449800.5	1.5	
	1989 VB	1.8648	0.4608	2.13	38.34	329.60	51.13	2449800.5	0.4	
	1989 UR	1.0801	0.3563	10.34	233.89	289.29	198.37	2449800.5	1	
	1989 UP	1.8637	0.4732	3.86	52.79	17.21	33.00	2449800.5	0.3	
	1989 JA	1.7704	0.4841	15.23	60.93	231.80	152.06	2449800.5	1.5	
	1989 DA	2.1623	0.5433	6.44	349.08	138.73	334.08	2449800.5	1	
	1989 AZ	1.6457	0.4682	11.76	295.06	111.63	1.15	2449800.5	0.5	
	1988 XB	1.4674	0.4816	3.12	73.02	279.79	228.74	2449800.5	1	
	1988 TA	1.5408	0.4786	2.54	194.49	104.57	163.78	2449800.5	0.2	
	1987 OA	1.4962	0.5956	9.02	179.69	235.38	22.98	2449800.5	0.8	
	1986 JK	2.7960	0.6806	2.13	62.17	232.40	311.67	2449800.5	0.6	
	1984 QY1	3.5976	0.9390	17.85	144.72	335.79	188.67	2449800.5	11	
	1983 VB	1.8189	0.4752	12.05	247.70	115.36	244.46	2449800.5	0.8	
	1983 VA	2.6106	0.6926	16.24	76.81	11.67	240.77	2449800.5	2	
	1983 LC	2.6304	0.7089	1.52	159.07	184.67	259.64	2449800.5	0.6	
	1979 XB	2.2622	0.7141	24.85	85.14	75.64	162.17	2449800.5	0.6	
	1978 CA	1.1246	0.2148	26.11	160.63	102.12	30.27	2449800.5	1	S
	1950 DA	1.6840	0.5023	12.08	356.28	224.26	203.55	2449800.5	3	
Hermes	1937 UB	1.6463	0.6236	6.13	34.11	91.85	27.19	2449800.5	1	
	6344 P-L	2.6270	0.6309	4.47	180.50	237.09	30.16	2449800.5	0.2	
	5025 P-L	4.2089	0.8947	6.34	354.67	151.44	341.82	2449800.5	5	

TABLE 3: AMORS

	Desig	a	e	i	Node	Peri	M	Epoch	Diam	Type
433 Eros		1.4582	0.2229	10.82	303.71	178.60	161.38	2449800.5	20.	S
719 Albert		2.5840	0.5393	11.24	183.96	155.07	42.87	2449800.5	2	
887 Alinda		2.4928	0.5594	9.27	110.09	349.81	136.26	2449800.5	5.4	S
1036 Ganymed		2.6597	0.5379	26.63	215.11	132.27	76.91	2449800.5	41	S
1221 Amor	1932 EA1	1.9196	0.4353	11.89	170.83	26.30	229.59	2449800.5	1	
1580 Betulia	1950 KA	2.1946	0.4901	52.12	61.68	159.31	289.57	2449800.5	7.6	C
1627 Ivar	1929 SH	1.8632	0.3967	8.44	132.61	167.41	291.73	2449800.5	7.0	S
1915 Quetzalcoatl	1953 EA	2.5362	0.5741	20.46	162.36	347.90	177.59	2449800.5	0.5	SMU
1916 Boreas	1953 RA	2.2731	0.4494	12.83	340.20	335.27	54.42	2449800.5	3	S
1917 Cuyo	1968 AA	2.1513	0.5039	23.94	187.77	194.26	259.00	2449800.5	6	
1943 Anteros	1973 EC	1.4302	0.2559	8.70	245.73	338.20	287.25	2449800.5	2	S
1980 Tezcatlipoca	1950 LA	1.7096	0.3649	26.85	246.03	115.29	313.20	2449800.5	13	SU
2059 Baboquivari	1963 UA	2.6490	0.5264	11.00	200.43	191.17	102.17	2449800.5	2	
2061 Anza	1960 UA	2.2654	0.5365	3.76	207.07	156.42	40.91	2449800.5	3	TCG
2202 Pele	1972 RA	2.2900	0.5125	8.78	169.71	217.20	166.86	2449800.5	2	
2368 Beltrovata	1977 RA	2.1046	0.4138	5.24	287.05	42.24	273.73	2449800.5	3	SQ
2608 Seneca	1978 DA	2.4906	0.5816	15.34	168.91	33.90	118.21	2449800.5	1	S
3102 Krok	1981 QA	2.1523	0.4475	8.41	171.70	154.31	109.06	2449800.5	1	QRS
3122 Florence	1981 ET3	1.7685	0.4227	22.17	335.53	27.55	155.48	2449800.5	6	
3199 Nefertiti	1982 RA	1.5743	0.2837	32.96	339.41	53.32	90.86	2449800.5	3	S
3271	1982 RB	2.1024	0.3949	25.00	158.35	158.66	51.69	2449800.5	2	
3288 Seleucus	1982 DV	2.0325	0.4573	5.93	218.11	349.24	168.15	2449800.5	3	S
3352 McAuliffe	1981 CW	1.8784	0.3694	4.77	106.87	15.59	175.37	2449800.5	3	
3551 Verenia	1983 RD	2.0932	0.4866	9.50	173.29	193.06	287.25	2449800.5	1	V
3552 Don Quixote	1983 SA	4.2340	0.7141	30.78	350.02	316.59	121.87	2449800.5	18	D
3553 Mera	1985 JA	1.6446	0.3203	36.76	231.95	288.85	282.42	2449800.5	2	
3691	1982 FT	1.7743	0.2839	20.37	348.24	234.61	161.62	2449800.5	5	
3908	1980 PA	1.9241	0.4587	2.17	261.18	125.72	146.52	2449800.5	0.8	V
3988	1986 LA	1.5446	0.3166	10.77	229.30	86.62	171.68	2449800.5	0.8	
4055 Magellan	1985 DO2	1.8201	0.3263	23.24	164.29	154.11	253.29	2449800.5	3	V
4401 Aditi	1985 TB	2.5762	0.5676	26.79	23.31	67.08	83.58	2449800.5	3	
4487 Pocahontas	1987 UA	1.7302	0.2966	16.40	197.55	173.72	99.68	2449800.5	1	
4596	1981 QB	2.2392	0.5188	37.12	153.80	248.30	354.00	2449800.5	2	
4688	1980 WF	2.2347	0.5143	6.41	241.03	212.91	96.71	2449800.5	0.5	QU
4947 Ninkasi	1988 TJ1	1.3696	0.1682	15.65	214.84	192.74	345.90	2449800.5	0.8	
4954 Eric	1990 SQ	2.0020	0.4481	17.47	358.12	52.01	188.99	2449800.5	12	
4957 Brucemurray	1990 XJ	1.5654	0.2189	35.01	254.29	97.46	115.89	2449800.5	4	
5324 Lyapunov	1987 SL	2.9591	0.6152	19.48	352.42	320.15	181.22	2449800.5	6	
5332	1990 DA	2.1635	0.4564	25.43	142.48	305.56	235.47	2449800.5	7	
5370 Taranis	1986 RA	3.3469	0.6318	19.01	177.19	161.11	142.58	2449800.5	5	
5587	1990 SB	2.3923	0.5483	18.09	189.88	86.19	110.92	2449800.5	7	
5620	1990 OA	2.1591	0.4222	7.84	128.31	152.95	177.25	2449800.5	1.5	
5626	1991 FE	2.1955	0.4543	3.86	172.87	231.07	168.09	2449800.5	4	
5646	1990 TR	2.1420	0.4375	7.90	13.61	335.37	162.24	2449800.5	5	
5653	1992 WD5	1.7942	0.3038	6.86	9.50	122.15	315.07	2449800.5	3	
5751	1992 AC	2.1045	0.4211	16.05	121.12	25.13	5.32	2449800.5	8	
5797	1980 AA	1.8924	0.4441	4.18	298.41	168.13	303.93	2449800.5	0.6	
5836	1993 MF	2.4438	0.5319	8.03	240.43	74.78	154.67	2449800.5	6	
5863	1983 RB	2.2220	0.5062	19.43	168.79	114.78	192.76	2449800.5	3	
5869 Tanith	1988 VN4	1.8121	0.3210	17.94	227.37	230.55	189.33	2449800.5	2	
5879	1992 CH1	1.6245	0.2893	21.57	145.27	355.45	183.08	2449800.5	1	
6050	1992 AE	2.2027	0.4363	6.40	87.90	284.53	17.30	2449800.5	3	
6178	1986 DA	2.8205	0.5823	4.29	64.41	126.87	321.62	2449800.5	4	
	1995 BK2	2.4417	0.5501	24.73	130.51	349.56	16.04	2449800.5	0.1	
	1995 BC2	1.9175	0.4304	5.02	328.01	81.19	55.76	2449800.5	2	
	1994 US	2.7182	0.5671	8.46	223.06	121.45	44.21	2449800.5	0.2	
	1994 TE2	2.3043	0.4548	5.70	198.07	182.14	46.33	2449800.5	0.2	
	1994 TA2	2.6781	0.5312	7.07	200.47	119.12	52.54	2449800.5	0.3	
	1994 TW1	2.5912	0.5768	36.03	2.92	62.19	17.94	2449800.5	5	
	1994 RH	2.2466	0.4414	18.92	330.99	91.81	23.17	2449800.5	3	
	1994 QC	1.3243	0.1179	13.87	161.92	94.08	197.80	2449800.5	0.6	
	1994 PN	2.3757	0.5400	46.05	112.54	233.88	40.75	2449800.5	2	
	1994 PC	1.5683	0.3173	9.45	123.89	256.52	75.95	2449800.5	2	
	1994 NK	2.3515	0.5387	5.67	119.54	128.48	82.34	2449800.5	0.4	
	1994 ND	2.1663	0.5160	27.19	102.14	227.88	68.20	2449800.5	1	
	1994 LW	3.1624	0.6195	23.02	240.44	54.41	41.52	2449800.5	2	
	1994 JX	2.7372	0.5793	32.68	52.23	192.21	65.48	2449800.5	1	
	1994 GY	2.6699	0.5318	12.46	33.43	189.95	72.14	2449800.5	2	

1994	EF2	2.2919	0.5176	23.31	345.75	123.68	123.38	2449800.5	2
1994	BB	2.0222	0.4257	1.14	122.19	335.84	154.30	2449800.5	0.1
1994	AW1	1.1046	0.0752	24.09	289.74	37.13	149.00	2449800.5	2
1994	AB1	2.8432	0.5915	4.52	66.49	342.39	104.86	2449800.5	2
1993	VC	2.7742	0.5330	3.20	241.94	177.04	102.41	2449800.5	0.3
1993	UD	1.3194	0.1942	22.78	24.46	254.66	68.33	2449800.5	0.4
1993	UB	2.2773	0.4602	25.02	30.83	20.78	138.90	2449800.5	2
1993	TQ2	1.9863	0.4198	6.04	13.01	77.24	158.63	2449800.5	0.4
1993	RA	1.9276	0.4186	5.70	171.27	265.28	158.66	2449800.5	0.8
1993	QP	2.3072	0.4693	7.24	296.70	46.55	159.58	2449800.5	1
1993	OM7	1.3398	0.2331	25.95	296.98	142.47	265.31	2449800.5	0.8
1993	MO	1.6261	0.2208	22.63	110.90	167.06	296.20	2449800.5	2
1993	HO1	1.9872	0.4165	5.90	22.23	104.98	290.34	2449800.5	2
1993	HA	1.2782	0.1442	7.73	182.76	263.47	234.13	2449800.5	0.4
1993	FS	2.2267	0.4247	10.13	178.73	20.82	211.32	2449800.5	0.4
1993	DQ1	2.0399	0.4911	9.97	313.03	344.41	144.45	2449800.5	2
1993	BU3	2.4061	0.5142	5.29	315.61	144.39	215.05	2449800.5	0.2
1993	BD3	1.6346	0.3748	0.88	312.96	168.86	12.77	2449800.5	0.02
1993	BD2	2.1230	0.3933	25.59	96.50	65.06	221.55	2449800.5	0.6
1992	UB	3.0658	0.5823	15.94	73.68	290.67	166.82	2449800.5	2
1992	TC	1.5657	0.2923	7.08	88.11	275.36	95.98	2449800.5	1
1992	SZ	2.1769	0.4599	9.27	3.74	314.60	292.98	2449800.5	0.4
1992	SL	1.6415	0.3339	8.59	0.41	344.50	75.71	2449800.5	1.
1992	OM	2.1935	0.4087	8.21	313.15	346.80	298.57	2449800.5	2
1992	NA	2.3910	0.5603	9.75	348.91	7.85	245.63	2449800.5	2
1992	LR	1.8310	0.4090	2.02	232.38	67.85	26.56	2449800.5	1
1992	JE	2.1895	0.4632	5.86	193.25	109.45	288.40	2449800.5	2
1992	BL2	1.6814	0.2300	36.86	297.15	23.40	311.09	2449800.5	4
1992	BA	1.3412	0.0676	10.48	139.64	107.17	255.11	2449800.5	0.3
1992	AA	1.9816	0.3897	8.29	102.15	354.30	54.79	2449800.5	2
1991	XB	2.9552	0.5867	16.29	249.74	172.00	233.78	2449800.5	1
1991	RJ2	2.2105	0.4279	8.91	171.39	150.33	36.09	2449800.5	0.6
1991	PM5	1.7194	0.2551	14.42	132.09	140.27	244.15	2449800.5	1
1991	OA	2.5081	0.5876	5.51	305.88	317.27	340.77	2449800.5	1
1991	NT3	1.8109	0.3041	13.86	286.78	292.75	226.14	2449800.5	5
1991	JG1	1.3732	0.1844	33.85	225.78	322.57	172.70	2449800.5	0.6
1991	JR	1.4032	0.2598	10.11	59.50	207.11	96.35	2449800.5	0.1
1991	FB	2.3675	0.5628	9.19	18.41	218.33	22.61	2449800.5	0.6
1991	FA	1.9790	0.4467	3.07	338.84	91.76	210.37	2449800.5	2
1991	DB	1.7163	0.4019	11.43	157.78	50.98	269.25	2449800.5	0.8
1990	VB	2.4433	0.5277	14.56	253.91	102.25	60.05	2449800.5	2
1990	UP	1.3253	0.1685	28.06	32.59	293.85	9.69	2449800.5	0.3
1990	SA	1.9579	0.4295	37.53	171.69	114.31	260.05	2449800.5	2
1990	KA	2.1987	0.4328	7.56	105.10	146.50	168.81	2449800.5	2
1990	BA	1.7403	0.3376	1.99	311.17	170.79	88.00	2449800.5	1
1989	RS1	2.3039	0.4817	7.18	174.03	180.86	205.91	2449800.5	1
1989	RC	2.3123	0.5138	7.38	139.68	181.09	213.16	2449800.5	1
1989	OB	2.6963	0.5594	7.91	289.02	71.72	84.97	2449800.5	2
1989	ML	1.2723	0.1364	4.37	103.83	183.10	350.60	2449800.5	0.5
1988	SM	1.6628	0.3433	10.92	0.38	312.92	30.25	2449800.5	1
1988	PA	2.1502	0.4077	8.21	161.74	136.95	41.55	2449800.5	2
1988	NE	2.1808	0.4424	9.93	253.53	354.81	42.48	2449800.5	0.8
1987	WC	1.3619	0.2336	15.83	51.27	308.10	261.24	2449800.5	0.5
1987	SF3	2.2541	0.5333	3.32	187.02	133.63	88.85	2449800.5	0.8
1987	QB	2.7927	0.5975	3.48	152.88	156.10	228.26	2449800.5	0.6
1987	PA	2.7172	0.5640	16.35	307.97	337.77	258.27	2449800.5	0.8
1986	NA	2.1260	0.4495	10.34	243.21	35.68	293.62	2449800.5	0.4
1985	WA	2.8345	0.6058	9.78	43.00	351.11	344.97	2449800.5	0.8
1983	LB	2.2865	0.4770	25.35	80.82	220.18	132.56	2449800.5	2
1982	YA	3.6952	0.6993	34.90	268.91	143.80	264.76	2449800.5	4
1977	VA	1.8642	0.3940	2.98	223.94	172.37	299.74	2449800.5	0.6
1977	QQ5	2.2256	0.4662	25.20	133.83	247.77	88.64	2449800.5	4
1972	RB	2.1499	0.4856	5.22	176.81	152.34	59.99	2449800.5	0.6
4788	P-L	2.6274	0.5501	10.98	176.92	97.14	69.97	2449800.5	2

Predicted Close Approaches

The following are some of the predicted close asteroid and comet approaches through the year 2020, supplied by Don Yeomans of the NASA/Caltech Jet Propulsion Laboratory.

NOTE: CA = closest approach distance to the Earth in Astronomical Units (150 million km)

Comets and asteroids passing within 0.1 AU of the Earth through 2020

Object	Date (TBD)	CA Distance	Absolute Magnitude	RA	DEC
1991 JX	1995 06 9.098	.0341	18.5	278	37
2063 Bacchus	1996 03 31.670	.0678	16.4	230	59
1991 CS	1996 08 28.419	.0620	17.5	53	-2
4197 1982 TA	1996 10 25.639	.0846	14.5	289	72
3908 1980 PA	1996 10 27.860	.0613	17.4	2	32
1991 VE	1996 10 29.543	.0853	19.0	296	-66
4179 Toutatis	1996 11 29.953	.0354	15.4	204	-22
1991 VK	1997 01 10.695	.0749	17.0	287	-18
6037 1988 EG	1998 02 28.914	.0318	18.7	77	-28
1991 RB	1998 09 18.475	.0401	19.0	170	-46
1989 UR	1998 11 28.689	.0800	18.0	4	-18
1992 SK	1999 03 26.265	.0560	17.5	28	41
1991 JX	1999 06 2.819	.0500	18.5	291	12
4486 Mithra	2000 08 14.365	.0466	15.4	112	-69
4179 Toutatis	2000 10 31.186	.0739	15.4	218	-21
1991 VK	2002 01 16.498	.0718	17.0	289	-24
4660 Nereus	2002 01 22.512	.0290	18.3	287	-13
5604 1992 FE	2002 06 22.264	.0768	17.0	157	-47
1991 BN	2002 11 14.726	.0775	20.0	325	19
1990 SM	2003 02 17.275	.0747	16.5	59	40
1991 JX	2003 05 20.681	.0922	18.5	301	-6
1990 OS	2003 11 11.448	.0250	20.0	194	40
1989 QF	2004 02 4.267	.0748	18.0	22	42
4179 Toutatis	2004 09 29.567	.0104	15.4	218	-60
1988.XB	2004 11 21.965	.0728	17.5	164	-1
1992 BF	2005 03 3.695	.0630	19.0	129	-62
1993 VW	2005 04 24.904	.0862	16.5	137	-24
1992 UY4	2005 08 8.424	.0402	17.5	359	12
1991 RB	2005 09 13.130	.0785	19.0	101	-1
1862 Apollo	2005 11 6.802	.0752	16.3	154	31
Schwassmann-Wachmann 3	2006 05 10.688	.0912	15.0	309	21
1991 VK	2007 01 21.507	.0679	17.0	291	-31
1862 Apollo	2007 05 8.638	.0714	16.3	329	-39
2340 Hathor	2007 10 22.238	.0600	20.3	278	-12

1989 UR	2007 11 26.357	.0406	18.0	117	-33
1989 AZ	2008 01 1.478	.0622	19.5	185	59
4450 Pan	2008 02 19.932	.0408	17.1	74	-21
1991 VH	2008 08 12.238	.0291	17.0	167	9
4179 Toutatis	2008 11 9.514	.0502	15.4	214	-22
1993 KH	2008 11 22.328	.0992	19.0	331	-12
1991 JW	2009 05 23.959	.0813	19.5	201	-23
1994 CC	2009 06 9.459	.0163	18.0	88	-39
1991 AQ	2010 01 29.143	.0892	17.5	26	35
1989 QF	2010 08 12.405	.0723	18.0	49	-4
1991 JW	2010 11 28.916	.0953	19.5	326	-2
1990 UN	2011 03 16.824	.0902	23.5	94	36
1990 SS	2011 03 17.375	.0994	19.0	126	50
Honda-Mrkos-Pajdusakova	2011 08 15.275	.0601	18.0	92	-67
1991 VK	2012 01 25.997	.0650	17.0	294	-37
4179 Toutatis	2012 12 12.277	.0463	15.4	21	1
1988 TA	2013 05 8.082	.0546	21.0	304	9
1984 KB	2013 11 11.545	.0790	15.0	118	-52
2340 Hathor	2014 10 21.895	.0482	20.3	89	25
1990 UA	2015 05 13.691	.0556	19.5	315	-3
1566 Icarus	2015 06 16.652	.0538	16.4	182	49
1994 AW1	2015 07 15.347	.0577	17.5	217	-23
1991 VK	2017 01 25.542	.0647	17.0	294	-38
Honda-Mrkos-Pajdusakova	2017 02 11.104	.0864	18.0	249	23
5604 1992 FE	2017 02 24.420	.0336	17.0	62	-74
1984 KB	2017 05 27.630	.0985	15.0	183	65
1991 VG	2017 08 7.351	.0568	28.8	314	-43
3122 Florence	2017 09 1.493	.0472	14.2	315	2
5189 1990 UQ	2017 09 26.762	.0611	17.5	278	-71
1989 UP	2017 11 4.241	.0471	20.5	97	10
3361 Orpheus	2017 11 25.690	.0607	19.0	340	-48
3200 Phaethon	2017 12 16.958	.0689	14.6	7	27
1991 VG	2018 02 11.915	.0473	28.8	43	47
1981 Midas	2018 03 21.889	.0896	15.0	101	32
4581 Asclepius	2020 03 25.616	.0705	20.5	84	24
1991 DG	2020 04 6.279	.0857	19.0	118	51
1990 MF	2020 07 23.929	.0546	18.7	169	44
1988 XB	2020 11 22.708	.0662	17.5	163	-1

R.A. and Dec. are the object's approximate right ascension and declination values at Earth close approach.

OCTOBER 27, 1997 VOL. 150 NO. 17

DREADFUL SORRY, CLEMENTINE

WASHINGTON BRUSHES OFF THE ASTEROID THREAT

BY LEON JAROFF

During the 3 or 4 billion years that it has existed on Earth, life has been devastated, and on occasion nearly wiped out, by the explosive impact of giant asteroids or comets. Now terrestrial life has finally evolved to the point where it is intelligent and capable enough to defend itself against the next such threats from space--if it has the will to do so.

That is why some scientists are so distressed by President Clinton's line-item veto last week of the $30 million that Congress had allocated for the Clementine II project next year. Clementine is a spacecraft that was to be launched in 1999 to approach an asteroid named Toutatis and send a camera-equipped rocket barreling toward it. The missile, after taking close-up pictures of Toutatis, would smash into its surface while Clementine recorded the impact flash and analyzed any ejected material. The goal was not only to test our ability to rendezvous with an asteroid but also to determine Toutatis' composition and mechanical strength--important considerations in designing weapons to ward off incoming comets and asteroids.

Reasons for the veto, an Administration spokesman explained, included concern that the project might violate the Antiballistic Missile Treaty, that it was a thinly disguised supplement to other Pentagon projects and more logically belonged in the NASA budget. Another--but unspoken--reason, say scientists familiar with the budget debate, is the "giggle factor," the tendency of many in government to scoff at the danger posed by asteroids.

Astronomers estimate that about 2,000 objects large enough to cause a global catastrophe are hurtling on paths that either intersect or come close to Earth's orbit. Yet only 200 or so of these have thus far been identified and tracked. Just last year, a previously unknown asteroid some 1,600 ft. across was spotted four days before it whipped by Earth, missing us by only

280,000 miles--a hairbreadth by astronomical standards. Had it struck Earth, scientists say, the explosion would have been in the 3,000-to-12,000-megaton range, roughly equivalent to the explosive power of all the world's nuclear weapons going off at once.

In an attempt to assess the danger, a few dedicated astronomers have been scanning the skies, borrowing time on large telescopes, building their own detectors out of off-the-shelf parts and barely scraping by on the $1 million or so that NASA contributes annually to the total effort. Their goal is to identify and determine the orbits of the still undiscovered "near Earth" asteroids. That would enable them to predict, sometimes many years in advance, the possibility of a disastrous encounter. Those predictions and knowledge gained from missions like Clementine II would give Earth's defenders time to mount the appropriate defense, using missiles to deflect or destroy a threatening intruder.

With a bit more funding and access to the Air Force's satellite-tracking telescopes, say astronomers, they could find and track the most threatening asteroids within a decade. The cost to taxpayers, they estimate, would be a few million dollars more a year. If you think of it as an insurance policy for the entire planet, it's a small price to pay.