Can Lasers Play a Rôle in Planetary Defense?

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Abstract. It is now well-established that a NEO in the 5 to 10-km size range extinguished the dinosaurs. Although such events have an impact interval on the order of 100M years, a method of rapid response to such a threat is crucial, since warning time is short. Objects in the 0.1 to 1 km size range may not be detected before approaching within 1 to 10 AU of Earth and, since their approach velocity may be 30-60 km/s, that situation leaves 100 – 300 days to respond. Although the most frequently suggested response to such a threat is a standoff nuclear detonation, physically delivered to the NEO, this paper finds significant advantages in retargeting, probability of success and even precise target location are possible with a high power laser alternative. Assuming a momentum coupling coefficient C_m = 3.5 dyn-s/J and detection at 6.3AU, a 770kW repetitive pulse 355nm laser (f = 1.7 ppm with 27MJ, 10ps pulses) will deflect a 200-m-diameter icy NEO sufficiently to avoid collision. The focusing mirror would need to be manufactured on the Moon.

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THE PROBLEM OF PLANETARY DEFENSE

It is now well-established that a NEO in the 1 to 5-km size range extinguished the dinosaurs. From a risk point of view, these objects are of two types: asteroids in stable orbits which can be tracked and long period comets. Among the latter, comet nuclei which have not yet been detected constitute the main hazard.

NEO's are not an "academic" problem. Direct impact by an Earth-crossing object of order 10km diameter will result in annihilation of most biota by the resulting firestorm and nuclear winter. Such objects have a kinetic energy release of order 30TT (teratons), create 10-km tsunamis[1] and magnitude 12 earthquakes. The last such event occurred 65M years ago.

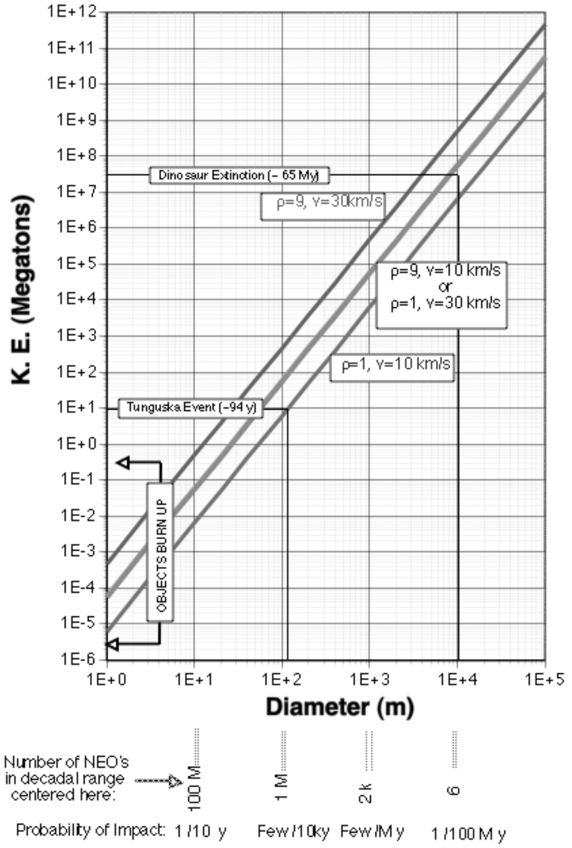
Beginning with the 1991 NASA/Los Alamos Workshop on Near Earth Object Interception [2-3], lasers have been considered a means for deflecting near-Earth objects (NEO's) discovered to be on a collision course with Earth [4-7]. However, majority opinion in such meetings has been that the most effective response is a standoff nuclear detonation, physically delivered to the NEO.

Aside from the lack of enthusiasm many nations might exhibit for the U.S. putting nuclear devices in orbit, the astrodynamics of delivery of the weapon to the NEO require Δv capabilities of order 100km/s, well beyond current capability. Further, even if delivery is successful, there is only one chance of success per delivery, so that many simultaneous launches would be necessary to give an acceptable probability of defending the planet.

There are significant advantages in retargeting, probability of success and even precise target location which are possible with the high-power laser alternative. What makes this possible is discarding earlier assumptions about arbitrary limits on imaging mirror size. With our choice of laser parameters, the laser and imaging mirror would be space-based, because of the size involved, the pointing stability required, and to avoid nonlinear optics effects in the Earth's atmosphere.

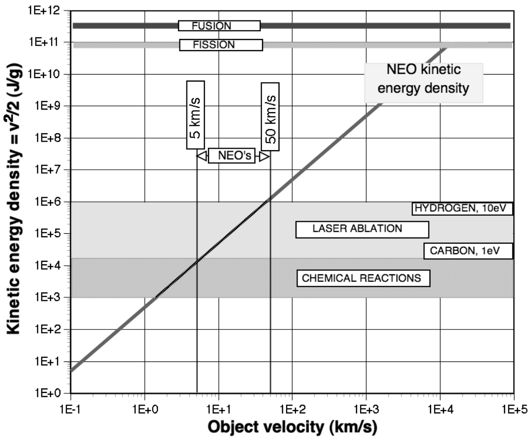
The Threat

Figure 1 illustrates the threat of near-Earth object (NEO) collisions with Earth.



(a). NEO kinetic energy vs. object diameter expressed as MT of TNT equivalent, for the densities of iron and of ice (the two NEO types).

FIGURE 1. Illustrating the threat posed by NEO collisions with Earth.



(b). NEO kinetic energy density at 60km/s exceeds that of chemical reactions by two orders of magnitude

(c). A 1938 photo of the devastation produced by the 1908 Tunguska incident [8]

In the 1908 Tunguska event, the impactor was probably an iceball about 80m in diameter. It leveled 2150 km^2 of Siberian forest (Figure 1.c.) [5]. Events such as this recur every thousand years or so. The event that formed the so-called "Cretaceous-Paleogene boundary," terminating the Mesozoic era and causing mass extinction of life on Earth was caused by impact of an object in the 10-km size range at the

Chicxulub site off the coast of present-day northern Yucatan. These events are infrequent – about one per 100My. Nevertheless, there is now no way to prevent another mass extinction if such an object were detected approaching Earth. The most worrisome aspect of the problem is detection, since “dirty snowball” objects typically have albedo of a few percent, and such objects in the 0.1 to 1 km size range might not be detected before approaching within 3 A.U. of Earth and, since their approach velocity may be 30-60 km/s, that situation leaves on the order of 100 days to respond.

NEO DETECTION

Detecting an approaching NEO will be a matter of good fortune, since whole-sky surveys capable of detecting very faint objects are not repeated frequently enough to give good warning. However, we assume a sensitive telescope is looking in the right direction. If the NEO has optical scattering coefficient ε into 2π sterradians, the range to detection $\mathbf{Z_{DET}}$ in units of A.U. is given by [3]

$$(1 + Z_{\mathrm{DET}})\mathbf{Z_{DET}} = 1.89\mathrm{E}-10\ \frac{D_{\mathrm{a}} D_{\mathrm{R}}}{\lambda}\sqrt{\frac{\varepsilon}{(S/N)}}\ . \tag{1}$$

In Eq. (1), S/N indicates the detector signal to noise ratio and D_{a} and D_{R} are the asteroid and detection receiver diameters. This relationship is plotted in Figure 2.

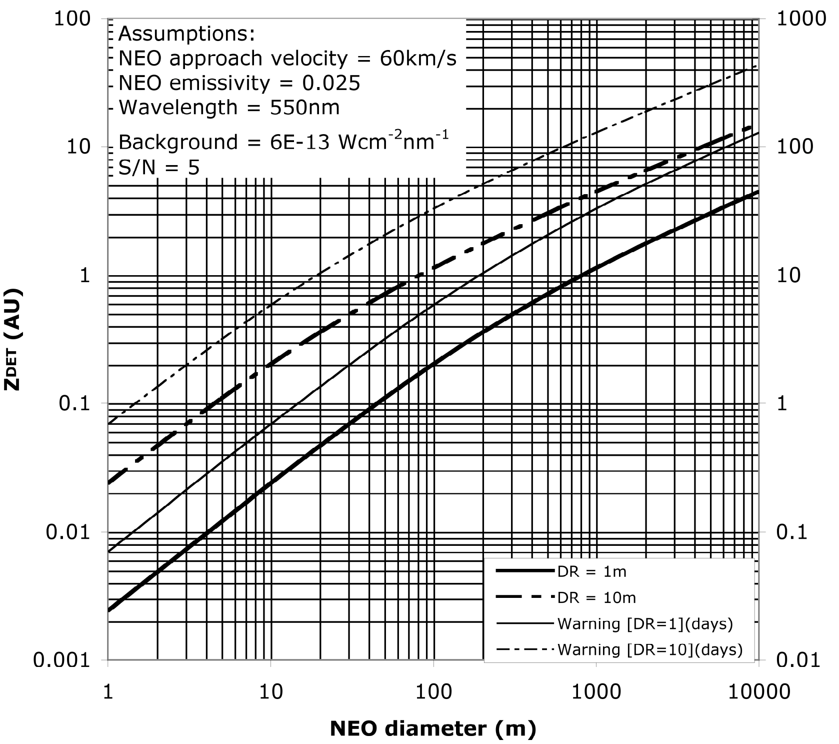


FIGURE 2. Warning time vs. NEO diameter for receiver diameters of 1 and 10 m.

Figure 2 shows that, for the “dirty snowball” objects, our warning time for an epoch-terminating asteroid collision with Earth could be as little as 100days. NASA’s planned WISE spaceborne infrared survey spacecraft [9] will mitigate this problem to a significant extent, increasing detection distance for large, dark objects by a factor-of-5 during its 6-month mission. WISE will have a wide 0.7 degree field of view and a 40cm aperture diameter. It detects dark objects at greater range because they are brighter in the infrared.

ASTRODYNAMICS OF PHYSICAL NEO DEFLECTION

If it is desired to fly a space platform to the NEO and push it aside with a standoff nuclear explosion [3], in the simplest astrodynamic sequence, three sequential maneuvers are necessary. Consider a 30km/s NEO which has been detected at a distance of 100days. Where $v_o = 30$ km/s is the NEO approach velocity, these are:

1) Accelerate through $\Delta v = v_o$

2) Decelerate through Δv

3) Reaccelerate in the reverse direction through Δv to match the NEO's velocity while carefully arming and placing the nuclear device.

The interceptor platform must be capable of a total $\Delta v = 90$km/s, which is beyond present capability. With chemical propellants, the rocket equation gives a launch mass to payload mass ratio M/m = of 6.6E7 for such a device. If the payload were 100kg, the rocket mass on the ground would be 6.5MT. If the vehicle acceleration is 0.1G (implying a liftoff thrust 200 times larger than has yet been realized), each of these three maneuvers can be completed in about one day.

More severe problems are the time required and the chances of error or failure. By the time the interceptor platform has pulled alongside the NEO in the above scenario, only 47 days remain. In addition, the first vehicle may arrive and its nuclear device fail to fire, or fail to impart the necessary momentum to the NEO, or, even if applied correctly in one pulse, could fracture it. This result is particularly likely for a snowball. The effect would be to convert the one target into many, making the problem far worse because of the "hohlraum effect" arising from multiple dispersed impactors converting the whole atmosphere into a glowing oven for several minutes back on Earth. One vehicle is not enough. Finally, multiple vehicles must be launched simultaneously, because failure is intolerable, and the associated cost is much larger than is usually assumed for one vehicle, probably in the multiple T$ range including development costs.

LASER NEO DEFLECTION

A laser has the crucial advantages of propagating its influence at the speed of light, and of instant retargeting and predictable, calibrated momentum exchange. The momentum is applied slowly, making fracture an impossibility and providing ample time for interaction diagnostics.

Our previous studies of this problem assumed side-on deflection. To do this, of course, appropriate illumination geometry requires the laser station to be located to one side of the NEO path, about one AU away from Earth. At least two stations are required, so that the laser station isn't on the wrong side of Earth when the NEO approaches. These studies were also hampered by limiting consideration to beam director mirror diameters no larger than 10km, which gave a spot size at range much larger than the NEO. Because of the tremendous mass of even a small NEO, time-average laser power required in these studies was of order 10GW for even a 40-m-diameter asteroid [5,7].

In this paper, we will discuss a new approach in which a 10-km-diameter beam director is assumed. We assume a 10-m-aperture WISE-type device which detects the object at 6.3AU, giving $t_o = 3.1E7$s (one year) to respond. The concept of operations is illustrated in Figure 3. Instead of sidewise deflection, we address the object head-on. The mirror diameter is chosen sufficient to create a spot size that is smaller than the object size during the entire period. The spot size

$$d_s = a\, M^2\, \lambda z / D \quad . \tag{2}$$

We use a hypergaussian beam profile,

$$I(\mathrm{r})/I_o = \exp\left[-(r/w_o)^n\right] \quad . \tag{3}$$

If $n = 6$, $a = 1.70$ [10], and we take beam quality $M^2 = 1.75$ and λ=355nm.

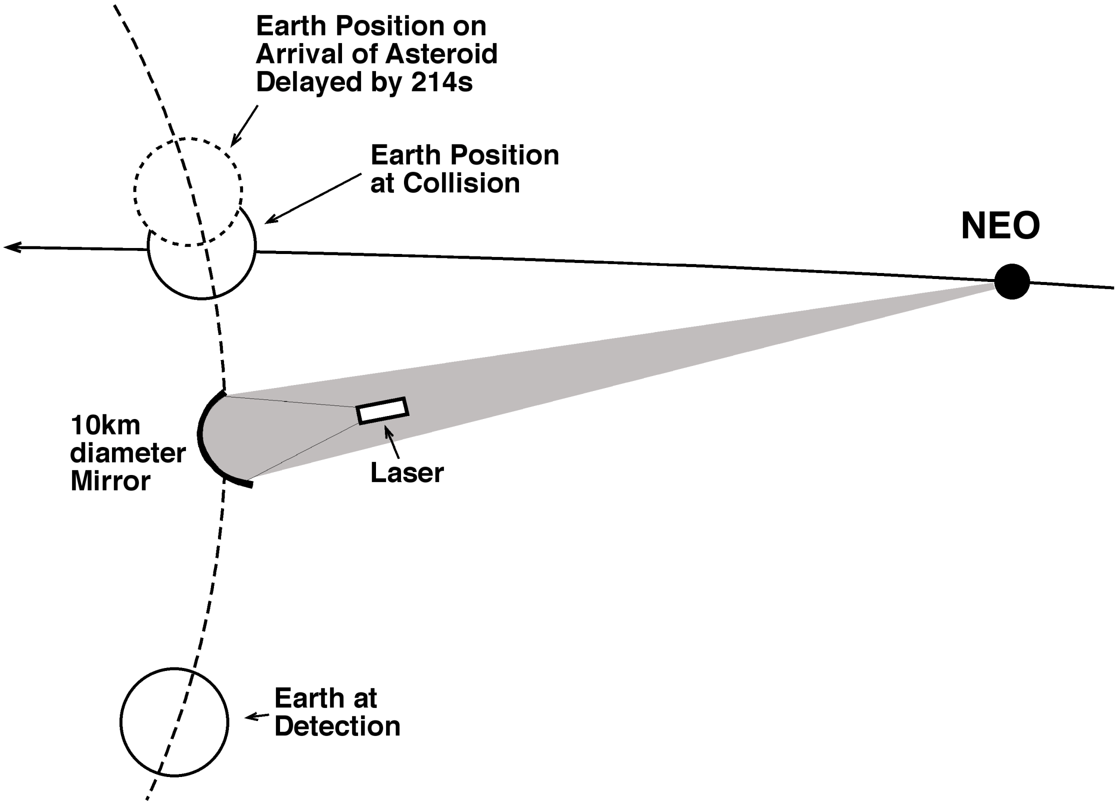


FIGURE 3. New concept for planetary defense (not to scale)

In the new concept, we detect the object as far out as possible, and illuminate it with a spot smaller than the object (100m diameter) using 10ps pulses to enhance plasma formation. The laser station is space-based, to avoid nonlinear optical effects in Earth's atmosphere and to permit stable deployment and nrad pointing jitter for the 100-km-diameter mirror required to create a 100m focal spot at 6.3AU. The Kepler exoplanet survey spacecraft already approaches this pointing jitter capability [11]. The goal is to slow the object by a few cm/s so that it arrives a few minutes later than it would have, permitting the Earth to get out of its way.

Since the Earth's orbital velocity is $v_E = 29.8$km/s, the necessary delay to clear one Earth radius r_E is a delay of

$$\Delta t = r_E/v_E = 214 \text{ s} \ . \tag{4}$$

We assume the NEO approach velocity is $v_o = 30$km/s, so the net change in velocity we need to apply over time t_o is

$$\Delta v = v_o \Delta t/t_o = 20\text{cm/s} \ . \tag{5}$$

In Table 1, we show what laser parameters would be necessary to provide this Δv to ice NEO's of diameter 200m and 1km. In the Table, we include a 7% correction factor for total energy on target to account for the ratio b/r_o

$$b/r_o = v_{max}/v_o = (2M_E G/r_E + v_o^2)/v_o = 1.07 \tag{6}$$

of the initial impact parameter b at detection to the distance of closest approach r_o, in order to insure that the object misses the Earth. In Eq. (5), M_E is Earth's mass, and G is the universal gravitation constant.

TABLE 1. Laser Parameters for Planetary Defense. NEO density = 1g/cm^3.
Laser wavelength = 355nm, pulse duration = 10ps, C_m = 3.5 dyn/W [12], and Δv = 20.4 cm/s.

NEO Diameter (m)	**C_m (dyn/W)**	**d_s (m)**	**Mirror Diameter D_b (km)**	**Fluence on Target (J/cm^2)**	**Laser Pulse Energy (MJ)**	**Laser Pulse Rate (Hz)**	**Laser Average Power**
200	3.5	100	10	0.34	27	0.029	770 kW
1000	3.5	100	10	0.34	27	3.6	96 MW

In this system concept, the mirror would be the dominant cost. From earlier work [13], we estimate total system cost at 30B$, which is not a lot to pay for defense of the planet. However, projected cost to launch the system into space from Earth is 1.1T$, mainly due to mirror mass. The only practical solution for a system this size is mining and manufacturing the mirror structure on the Moon, which would reduce launch cost to 48B$ and total system cost to 78B$.

DISCUSSION

With adequate planning and a willingness to invest proportional to the potential cost to life on Earth, the laser alternative offers advantages to nuclear explosive deflection. These are the ability to deflect an epoch-ending NEO gradually and safely, the ability to project a calibrated, retargetable defensive capability at the speed of light, and avoidance of nuclear devices in space.

ACKNOWLEDGMENTS

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