Numerical Models of Mitigation Options for Hypothetical Threat Object 2023 PDC

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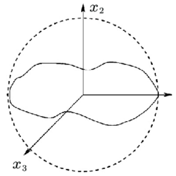
We present simulations of nuclear mitigation options for the hypothetical threat object 2023 PDC, based on Epoch 1 scenario inject. The estimated diameter is 220-660 m, with a median size of 470 m. The worst-case scenario orbit provided is challenging for kinetic impactors, potentially requiring multiple launches per attempt. Nuclear explosive devices may be an important alternative in such cases, permitting a comparable amount of energy to be delivered in one launch vehicle, in either a mitigation or disruption attempt. Here we use the RAGE (Gittings, 2008) hydrocode and SESAME EOS database (Johnson, 1994) to simulate the response of the threat object to nuclear explosive devices of different yields at different stand-off distances, and document options that could be viably delivered under this scenario's launch constraints.

APPROACH: We follow Schaefer et al. (1994) to calculate the maximum possible **Δ**v from a stand-off nuclear burst using conservation of energy arguments, and assuming a requirement for even irradiation of the surface to provide a homogeneous force across the target. We estimate the amount of energy it would take to disrupt and disperse the object such that the largest remaining fragment is half the size of the original body using the methods of Dobrovolskis and Korycansky (2018). With these upper bounds in mind, we then calculate the **Δ**v imparted to targets within the estimated diameters and compositions of the 2023 PDC threat object Epoch 1 by a 1 Mt energy burst.

This method is intended to be a quick upper-bound estimate. If this model says it is NOT possible to achieve a given **Δ**v, or disrupt and disperse a given target with a given yield at a given HOB, we make this assessment with medium confidence, because the momentum of the target may be unexpectedly enhanced by phenomena like massive fragments being blown off with the vapor, fragmentation, or exposure and sublimation of previously unknown subsurface volatiles. If the model says it is possible, with low confidence, because we expect that the energy absorption by the target will not be as efficient as this model predicts.

UPPER BOUND ΔV ESTIMATE METHODS: We begin by modelling the threat object as a sphere of radii given in the scenario inject. A sphere with the same radius as the semi-major axis of an irregular small body is called a Brillouin sphere.

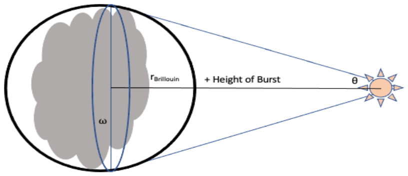
The "ideal" height of burst (HOB) is that which maximizes the fraction of the surface area of the target's Brillouin sphere which would be irradiated by the burst, and also maximizes the flux through that solid angle, ω.



Right: Diagram of a Brillouin sphere from Cui, Pingyuan & Qiao, Dong. (2014).

We use the method of Shafer et al. (1994) to find the ideal HOB:

$$\tan\theta = \frac{r_{Brillouin}}{HOB - r_{Brillouin}} \rightarrow HOB = 0.417 r_{Brillouin}$$



The fraction of the energy emitted by the nuclear burst that passes through the solid angle subtended by the target's Brillouin sphere is the burst fraction. At the ideal HOB, this is about 1/3.

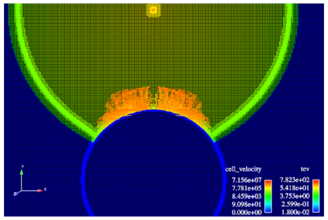
The maximum target mass that could possibly be vaporized by the amount of energy irradiating the target is

$$m_v = bf * Y\left(q * (T_v - T_i)\right)$$

where bf is the burst fraction, Y is yield, q is the specific heat of vaporization of the target, T_v is the vaporization temperature, and T_i is the initial temperature, omitting the liquid phase under vacuum.

UPPER BOUND Δv: Assuming the maximum amount of material has been vaporized just to the vaporization temperature, we use a 5/3 gamma-law gas approximation to estimate the force of the vaporized material decompressing and pushing against the remaining solid threat object to estimate an upper bound on **Δ**v.

HYDROCODE Δv : We model the nuclear standoff burst in RAGE as a small iron sphere (SESAME EOS 2140, Opacity 12143) and give it the internal energy of the intended burst yield, 1 Mt. The iron sphere is allowed to glow and explode according to the radiation hydrodynamics equations in RAGE. We then extract the momentum imparted to the hypothetical threat object and calculate **Δ**v.



DISCUSSION: The results table below show our model predictions for an upper bound on the **Δ**v possible from a one megaton nuclear stand-off burst, Max **Δ**v, the amount of energy required to disrupt and disperse an object, Q^*_D , and **Δ**v predicted for each case using the RAGE hydrocode.

In the last column we assess the possibility of mitigating the 2023 PDC threat object if it is like the assumptions listed for each case and is on the trajectories provided by CNEOS in the Epoch 1 exercise inject.

Q^*_D is greater than 1 Mt for all cases, so we do not predict disruption and dispersion from a 1 Mt stand-off burst when using the methods in Dobrovolskis and Korycansky (2018). These methods are preliminary and would benefit from further development and validation.

Another heuristic used to avoid unintentional disruption is limiting the **Δ**v to 1/10th the escape velocity of the threat object. The maximum possible **Δ**v > 0.1 v_{esc} for all cases. The hydrocode **Δ**v predictions are below 0.1 v_{esc} for some of the cases below. Where **Δ**v >> 0.1 v_{esc} , we color the cell amber to indicate caution. We color the cells green when **Δ**v is of order or less than 0.1 v_{esc} .

In cases where the NASA/JPL NEO Deflection App says that the hydrocode **Δ**v is insufficient, but **Δ**v ~ 0.1 v_{esc} , we note that multiple attempts may be required, but are feasible. For the cases with a disruption risk, it may be possible to increase stand-off distance to decrease the energy imparted to the threat object.

MODEL RESULTS

Case	d [m]	ρ [g/cm^3]	Type	mass [kg]	0.1*v_{esc} [cm/s]	Max dv(1Mt) [cm/s]	Q^*_D [Mt]	Hydrocode Δv [cm/s]	Possible with 1 Mt ?
Easiest	220	1.7	C	9.5E+9	1.1	3.84E+03	5.38E+02	1.81E+02	Yes, Disruption Risk
Hardest	660	8	M	1.2E+12	7.0	7.12E+01	6.83E+04	1.42E+00	Multiple Attempts Required
Median	470	2.1	S	1.1E+11	2.6	3.26E+01	6.48E+06	1.50E+01	Yes, Disruption Risk
Likely Small	220	2.3	S	1.3E+10	1.3	2.90E+02	7.27E+02	1.34E+02	Yes, Disruption Risk
Likely Large	660	1.7	C	2.6E+11	3.3	1.42E+02	1.45E+04	6.69E+00	Yes
Didymos-like	780	2.37	S	5.2E+11	4.3	3.79E+02	7.50E+02	3.29E+00	Yes
Bennu-like	490	1.19	C	7.3E+10	2.0	3.47E+02	5.94E+03	2.34E+01	Yes, Disruption Risk