Comet Threat Mitigation Approaches & Challenges

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[Abstract] Comet threat mitigation has either been ignored or folded in with asteroid deflection options. But comets represent a distinctly different threat and it would be extremely irresponsible to not address each threat separately. In general, comets are larger and faster than asteroids and can cause significantly greater damage and produce terrestrial mass extinctions. Comets, especially long-period comets from the Oort cloud, can appear with little advanced warning and from any direction (even high inclination orbits). The key difference between comets and asteroids lies in NEO composition. A comet mitigation approach should exploit this inherent difference and focus on fracturing a comet. This will result in increased surface area exposed to volatile outgassing. Fracturing a comet will permit solar radiation to amplify the damage effects. Under the suns influence, comet fragments will arrange themselves into a natural order, similar to a string of pearls. The fragment separation can significantly reduce or eliminate the planetary threat. Due to the gravity of this type of threat, one should use the most appropriate tool available. In this case, the only device capable of fracturing a large comet with a minimal time window (a few months) is a nuclear weapon. The delivery device would derive from a fusion of existing satellite and missile technology. Significant technology limitations must be overcome to counter this threat. Key technology development areas include: long range space-based precision detection and tracking systems capable of streamlining the resolution of impact uncertainties, advanced rocket motor design capable of achieving 50 km/s and very precision proximity fuze design with accuracies greater than ± 2.5 μs and/or the development of high speed impact triggers.

Nomenclature

d	=	diameter of the impactor (asteroid/comet)
D	=	density of the impactor
E	=	kinetic energy released from an impact
v	=	velocity of the impactor relative to Earth

I. Introduction

COMET threat mitigation has either been ignored or folded in with asteroid deflection options. But comets represent a distinctly different threat and it would be extremely irresponsible to not address each threat separately. The scope of this white paper will primarily focus on a mitigation approach to neutralize a comet threat. This paper will conclude with a brief discussion on related asteroid mitigation approaches that can be added to the toolset of available options.

II. Threat Divergence

Near Earth Objects (NEO) comprise Long-Period Comets (LPC), Short-Period Comets (SPC) and Asteroids. NEO pose a collision threat with Earth which can produce high levels of shock waves (atmospheric, ground, water) and the release of thermal and electromagnetic energy. The amount of kinetic energy released on impact (E) is a function of the diameter of the asteroid/comet (d), the velocity of the impactor relative to Earth (v), and the density of the impactor (D). Equation (1) defines the kinetic energy release expressed in megatons of TNT equivalent, where d is expressed in meters, v is expressed in km/s, and D is expressed in g/cm^3.

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$$E = 6.256 \bullet 10^{-8} d^3 v^2 D \qquad (1)$$

The derived formula assumes that 1 megaton of TNT is equivalent to 4.185 x 10^{22} ergs. This estimate is based on the assumption that the impactor is spherical in shape and a non-binary system. Many asteroids and comets have irregular shapes, which can affect impact energy calculations. Approximately 16 percent of Near Earth Asteroids larger than 200 m in diameter are binary systems.[1]

Comet density ranges from that of a fluffy snowball (0.1 g/cm^3) to the density of sheets of ice and dirt (2.0 g/cm^3) with the majority falling in the 0.5 to 1.0 g/cm^3 range based on delay Doppler radar analysis.[2] Asteroids range from 1 to 7 g/cm^3, with the majority around 2 g/cm^3. Typical impact velocities are roughly 20 km/s for asteroids and SPC and roughly 50 km/s for LPC. [†]

The kinetic energy equation shows that released energy levels are highly sensitive towards NEO size (diameter component is cubed), somewhat sensitive towards NEO speed (velocity component is squared) and less sensitive towards NEO density (density is a linear component). In general, LPC because of their larger size and higher speeds produce greater impact energy release than asteroids even though the comet's density is less.

Both comets and asteroids pose a danger to life on Earth. These objects differ in composition, speed, solar interaction, and orbital paths. Comets represent a greater danger because:

- Comets come into our Solar System from further out, by the time they cross the Earth's orbit, they are traveling much faster than asteroids. As a result, comets possess significantly greater amounts of kinetic energy.
- Asteroids are found in well-established orbits around the Sun and can be monitored over many orbits and the future impact risk can be assessed and mitigated. Comets arrive unpredictably from the outer parts of the solar system.
- The trajectory of comets is less predictable because they are influenced by the effects of the volatile outgassing, which will produce great jets that will erratically alter the comet's trajectory.
- Many comets are significantly larger than asteroids and as a result more destructive to mankind. There are significantly greater numbers of large comets than large asteroids. There are approximately 1.5 million asteroids greater than 1 km across in the main asteroid belt.[‡] It is estimated that 1 billion comets exist in the Kuiper Belt (of which 100,000 are larger than 100 km across), and 7 trillion comets exist in the Oort cloud.[3] Some of these comets are behemoths, which are several hundred km across.

Comets are very fragile, with little internal strength and a very low mass density. Comets are like huge dirty snowballs, conglomerates of water ice and rocky material formed in the early days of the solar system. Comets are composed of ice, clay and organic matter, including hydrocarbons in the form of an oil-like tar.[4] When a comet comes within 400 million km of the Sun (a little bit beyond the orbit of Mars); the sunlight is strong enough to start evaporating the ice in large quantities. Water, ammonia, methane, nitrogen, carbon monoxide and carbon dioxide ice change from a solid to vapors. Since the ice and rock are intimately mixed, the warming and evaporating ice produces great thermal and physical stresses on the body of the comet nucleus. Under normal circumstances, vapor and tiny dust grains are all that fly off the surface of the nucleus. When that happens, we see a comet with a long tail, such as those of Hyakutake and Hale-Bopp in the late 1990s. The NASA Solar and Heliospheric Observatory (SOHO), observed over 10,000 tons of water vapor per hour pouring off Hyakutake's comet nucleus.[5] Occasionally, however, the thermal stresses caused by solar warming become so great that entire chunks of the nucleus are ejected.

Comets possess an inherent weakness due to material composition that can be exploited for their destruction. The heat released from a nuclear weapon exploded in the interior of a comet will transform ices into high pressure gases and in combination with ground shock effects can fracture a comet. Fracturing a comet will permit solar radiation to greatly amplify the damage effects by increasing the surface area exposed to volatile out-gassing. Under the energy of the sun's heat, the out-gassing will work like a jet engine thrusting trailing comet fragments into a different trajectory. Comet fragments will arrange themselves into a natural order, similar to a string of pearls.

[†] Private correspondence between J. A. Marusek and Dr. Steve Ostro (NASA Jet Propulsion Laboratory (JPL)).
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III. String of Pearls

Under the influence of solar heating, comet fragments will arrange themselves into a natural order, similar to a cosmic string of pearls. As the lead fragment outgases, the dust and vapors will impact trailing fragments causing the structure to separate into a line over time.

In 1993, comet Shoemaker-Levy 9 fractured into over 25 pieces and these fragments formed naturally into a string of pearls. Beginning in 1995 comet 73P/Schwassmann Wachmann 3 began to fracture. The breakup accelerated on April 18, 2006 resulting in 64 comet fragments that recently flew by Earth. These fragments ordered themselves into a string of pearls. In July 2000, Comet Linear (C/1999 S4) broke apart into 16 fragments forming a string of pearls. In July 2002, comet 57P/du Toit-Neujmin-Delporte fractured into 20 pieces forming a string of pearls.

Under the influence of gravitational forces and solar heating, comets will fracture into pieces and eventually over time will decay to dust (meteorite) streams. One example is the Kreutz Sungrazers. The sungrazers share an elliptical orbit that brings some of the fragments less than 50,000 km from the Sun. Doug Biesecker (NASA Goddard) estimates currently 20,000 comet fragments comprise the Kreutz Sungrazers family. Over 800 Kreutz sungrazing comets have been cataloged since 1996 with the help of the Solar and Heliospheric Observatory (SOHO). The nucleus of the original comet may have been as wide as 100 km. Dr. Brian Marsden of the Center for Astrophysics speculated this parent body had been observed to fracture in two in 372 BC by the Greek historian Ephorus. Comets formed from this breakup includes the Great September Comet C/1882 R1 which itself broke into 6 fragments in 1882; comet Ikeya-Seki C/1865 S1 which broke into 3 fragments in November 1965; comet White-Ortiz-Bolelli C/1970 K1; comet Pereyra C/1963 R1 which appeared to split in two on November 9, 1963; the Eclipse Comet of 1882 (comet Tewfik X/1882 K1) and the Great March Comet of 1843, C/1843 D1. The take away from these observations is that even great comets 100 km in diameter can fracture and be broken down and neutralized.

IV. Comet Mitigation Approach

The proposed comet mitigation system consists of a space-based detection system and ground based interceptors. The space-based detection system would generally conform to the system proposed by Dr. R. E. Gold in 1999.[6] The nuclear tipped interceptor would be a hybrid, blending elements of a strategic nuclear missile technology and spacecraft technology.

A. Satellite Detection System

The greatest mitigation challenge is from LPC that appears at random from the Oort cloud. Generally, comets have very low albedo; which make them difficult to detect optically. However, as they heat up in the inner solar system, they will begin to out-gas forming extensive clouds of dust and gas known as "comae", which makes them fairly easy to detect. Comets start to brighten markedly when they reach a heliocentric distance of 3 Astronomical Units (AU) from the Sun. Comets travel at speeds near 50 km/s. At this rate, they could impact Earth less than 70 days after they first begin to brighten.

In 1999, Dr. Gold proposed a space based detection system composed of approximately 4 Sentries (detection spacecraft) in heliocentric orbit around the sun at a distance of 0.7 AU.[6] The system would detect the full range of threats (asteroids and comets greater than 0.1 km), compute orbit determination, produce perturbation analysis and forward the cataloged information to ground stations.

Space based detection systems offer several advantages over ground based systems. These include:

- *Full hemispherical sky coverage*. A system of space based detectors can provide full hemispherical sky coverage. Ground based imagers are generally limited by available declination coverage (Approximately ±30° in longitude and ±60° in latitude). Ground base systems have a significant blind spot created by the sun. Ground based systems may not detect an incoming LPC. Since no a priori knowledge of Oort cloud LPC orbits exists, the maximum impact warning time is from the time that it is first detected. This will generally occur when the comet begins to brighten (~ 70 days prior to impact), shorter if it is coming from the direction of the Sun. Late detection times would dramatically limit any mitigation approach. A space based detection system would push out the detection window up to 9 additional months.
- *Enhanced detection time*. Space based imagers can operate 24/7. Ground based imagers are limited to night time operations (between 3 hours after astronomical twilight to 3 hours before dawn).
- *Unobstructed view*. Ground based imagers are limited by reflected light from the moon.
- *Unaffected by poor weather*.

- *Dedicated resource*. Ground based imagers resources are shared with other Agencies.
- *Greater sensitivity*. Ground based imagers are affected by atmospheric extinction and background light.

Development of a space based detection system is relatively low risk venture with most components available using existing technology.

B. Interceptor Missile

The interceptor missile would need to achieve speeds of 50 km/s; which is hinged on the development of a new type of rocket motor, the Variable Specific Impulse Magnetoplasma Rocket (VSIMR).

The missile should be designed for ground based launch – boost to orbit followed by a smooth transition to VSIMR propulsion. The advantages of this approach are:

- Cuts down the complexity of the mission.
- Eliminates time window required for spacecraft assembly in space.
- Eliminates need to preposition spacecraft in orbit indefinitely.
- Allows tighter control and security of warhead component.

The interceptor missile should be capable of mid-coarse guidance controlled from Earth and final intercept terminal guidance and control built within the interceptor. A recent NASA mission bears striking similarities to this proposed mission. In the "Deep Impact" mission, a 371 kilogram impactor was slammed into Comet 9P/Tempel 1 on July 4, 2005 with a closing velocity of 10 km/s. This proposed comet mitigation mission would require targeting with a closing velocity approximately 100 km/s or greater.

Electrical power demands for the VSIMR are great and a nuclear reactor has been proposed to couple to this rocket. If this approach is implemented in the final rocket design, then the reactor could provide all the electrical power during the flight of the interceptor missile. Otherwise, electrical power could be provided by solar arrays combined with rechargeable battery packs.

The only way of preventing a large comet or asteroid from striking Earth on a short notice would be to use a nuclear device. That is the only means to generate sufficient energy to counter this threat.

The optimal mitigation approach for a large comet is an interior nuclear detonation. The logic is as follows:

- A comet is composed of a high percentage of various ices. The heat from a nuclear explosion will transform the ices into a gaseous state that can work to fracture a comet, in a manner similar to a steam boiler explosion.
- When comparing a standoff detonation, a surface detonation, and a subsurface detonation; the latter provides the greatest effective force and places the most thermal energy into the comet.

The nuclear warhead would require a shell to protect it while the warhead drives deep into the comet's interior and an impact trigger to initiate the nuclear reaction using the impact shock pulse.

A comet mitigation effort could easily require multiple engagements. As the comet fractures after the first engagement, the swarm of fragments will begin to order themselves into a structure similar to a sting of pearls. This is a natural structure. As the leading fragment outgases, the dust and vapors will impact the trailing fragments causing the structure to separate into a line over time. This structure facilitates ordered follow-on engagements. The leading edge of the comet string of pearls should be the focus of subsequent engagements since these particular fragments pose the most severe impact threat to Earth. Further fragmentation of the leading comet fragment will create more fragments and enhance greater separation of the string of pearls.

It should be noted that the fragments of the Shoemaker-Levy 9 comet hit Jupiter like bullets from a Gatling gun. The size of Earth is significantly smaller than Jupiter and the gravitational field projected by Earth is significantly less than that of Jupiter. As a result the same scenario does not apply. Many of the trailing fragments will glide past Earth missing the impact time window.

Example of a Theoretical Interceptor Engagement

Action	Result
Pre-Engagement:	One Large Comet
First Engagement (First Missile)	Lead Comet Fragment A, Trailing Comet Fragment B

Second Engagement	Lead Comet Sub-Fragment C, Comet Sub-Fragment D, Comet Fragment B, Trailing Comet Sub-Fragment E
Third Engagement	Lead Comet Minor Fragment F, Comet Minor Fragment G, Comet Minor Fragment H, Comet Sub-Fragment D, Comet Minor Fragment I, Comet Fragment B, Comet Minor Fragment J, Trailing Comet Sub-Fragment E
Fourth Engagement	Lead Comet Minor Fragment F, Comet Minor Fragment G, Comet Minor Fragment H, Comet Minor Fragment K, Comet Minor Fragment L, Comet Minor Fragment I, Comet Minor Fragment M, Comet Minor Fragment N, Comet Fragment B, Comet Minor Fragment J, Trailing Comet Sub-Fragment E.

The first engagement targets the large comet and splits it in two. The second engagement targets the lead fragment A and splits it into 3 sub-fragments. The third engagement targets the leading sub-fragment C and splits it into 5 minor fragments. The final engagement targets sub-fragment D and fractures it into 4 minor fragments. The end result is Minor Comet Fragments F, G, and H impact Earth producing only local damage. Two fragments impact the ocean and one hits land. The other fragments fly past Earth. Without the engagement, the impact from a large comet produces extensive global damage and loss of life bordering on a major extinction event.

1. VSIMR

Long period comets can travel at speeds of 50 km/s. If an imminent threat (impact time – months) should materialize, it will be very important to quickly move the engagement as far away from Earth as possible in order to maximize the exposure time for solar heating in order to spread out the comet fragment chain. This cannot be done with conventional chemical rocket engines because they are limited to speeds of ~ 10 km/s. It calls for the development of a new type of rocket motor, one that can achieve speeds of at least 50 km/s. Several rocket motor designs have been studied over the years including: the Stationary Plasma Thruster (SPT) also referred to as the Hall thruster, the MagnetoPlasmaDynamic (MPD) also called the Lorentz-Force Accelerator (LFA). But these designs have limiting factors for this type of mission. NASA has been exploring a rocket design called the VASIMR since the 1980's. This design offers three distinct advantages. VASIMR can produce speeds of 10-300 km/sec. And as a result can shorten the time till engagement significantly. The rocket can vary or modulate its thrust (plasma exhaust) to optimize acceleration throughout the mission. As a result, this thruster is capable of maneuvering to final intercept. The design does not utilize electrodes for plasma production or ion acceleration, so that the thruster lifetime is not limited by electrode erosion.

VASIMR uses radio waves and magnetic fields to ionize a propellant and accelerate it into a focused plasma beam. This rocket is designed using 3 modules. In the first chamber (helicon plasma source), a gas (typically hydrogen) is injected into the first cell where it is ionized into a cold plasma. In the central chamber (ion cyclotron-resonance heating (ICRH) module), the plasma is heated to temperatures $\sim 10^7$ degrees K and the proper density using radio-frequency excitation and ion cyclotron resonance. In the last module (magnetic nozzle) the plasma is magnetically and gas-dynamically exhausted by the aft cell to provide modulated thrust.[7]

The VASIMR has been proposed for the Mission to Mars program. Development of this rocket design can achieve two goals, the second being Planetary Defense.

2. Impact Trigger

In order to achieve a subsurface detonation, the interceptor missile will require an impact detonator - a device that uses the force of the impact to drive the Uranium core together to generate a nuclear explosion and protects the core for a sufficient period of time to allow the nuclear reaction to occur. In general, the nuclear missile with a closing velocity of 100 km/s will vaporize upon impact with the comet. The impact detonator will need a hardened shell that will survive for a few microseconds. During this time, the shell will drive deep within the comet. The shell construction might take a layered design, such as found in the reinforced carbon-carbon tiles used on the space shuttle. It might be composed of layers; similar to the construction used in tank armor, such as glass sandwiched between layers of depleted uranium.

V. Phased Implementation for Comet Mitigation

The satellite detection system has low development risk and it is recommended this system be developed in the initial phase. The interceptor carries several elements that are either at or beyond the leading edge of technology. Research and development of these components will drive development cost and risk high. The second phase (development of interceptor missiles) should be delayed until the technology matures and should hinge upon successful development of VSIMR.

There have been significant improvements in imaging and computer technology since 1999 when Dr. Gold proposed the space based detection system. These improvements should be incorporated into the improved design.

The following table provides my assessment of technology development risks:

Elements	Low Risk	Medium Risk	High Risk
Space Based Detection System	X		
Interceptor Missile			
- VSIMR		X	
- Rocket Booster	X		
- Mid-Coarse Guidance Control	X		
- Terminal Guidance & Control		X	
- Electrical Flight Power	X		
- Warhead Enclosure & Impact Trigger		X	

VI. Asteroid Mitigation Approach

This white paper is focused on mitigating the most difficult threat, that posed by an LPC and SPC. But elements of this proposed system may be useable to mitigate asteroid threats. The nuclear option is the only proposed system capable of engaging a short reaction time threat.

Two approaches are currently on the table for asteroid threat mitigation: destruction, deflection. Several scientists have opted towards the deflection approach over concerns that a fragmented asteroid might produce greater damage to Earth than the impact from a parent body. As a result, they have pushed the community to opt out of the nuclear option. This decision is based on conjecture and the choice of mitigation approach should be evaluated through actual testing. There is reasoning to conclude the opposite effect may take place. "Though many critics state that fragmenting an object could cause more damage than the single body would, the increased surface area created by fragmenting a body allows atmospheric friction to erode more of the threat before impact, thus lessening the energy released from the bodies at impact".[6]

To deflect an asteroid using a nuclear tipped interceptor missile, a high precise proximity fuze that controls the trigger on the stand-off detonation would need to be developed. To avoid the danger of fracturing the asteroid, the nuclear device would need to be detonated about 4 km from the asteroid's surface.[4] According to Johndale Solem, a mathematical physicist at Los Alamos; this distance represents the optimal nudging with the least chance of splintering. This high precision proximity fuze would be a critical component. This level of required accuracy, ~1.6 km, with a missile/comet closing velocity of 100 km/s, would mean the detection & trigger must be accurate to ± 2.5 μs. The limit of current missile technology using pre-trigger on intercept is ~2 km/s. At 100 km/s, if an interceptor designed for a stand-off detonation should strike the comet, the warhead could be vaporized. Also if the pre-trigger is off by a few microseconds, the energy imparted to the comet would be weak and ineffectual. Development of this high precision proximity fuze carries a very high technology risk because of the accuracies required.

For asteroid mitigation, neither approach (destruction, deflection) using interceptor missiles should be completely ruled out at this stage but rather subjected to actual testing as the technology barriers are eliminated.

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