

A New Global Risk: Large Comet's Impact on Sun Could Cause Fires on Earth

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There are several scientific papers that claim that the variability in luminosity of young stars can be explained by the collisions of these stars with comet-like bodies, and that during such collisions, energy release would be rapid and explosive in the upper layers of the solar atmosphere (similar to the explosion of the Chelyabinsk meteorite).

Furthermore, it is known that Kreutz comet progenitor with a diameter of 100-200 kilometers passed at a distance of 1.3 solar radii from the Sun around 2,300 years ago. Due to the very high escape velocity at the Sun, a body falling from infinity would have a velocity of 618 kilometers per second at its surface. This gives us energy estimates: when a body with a diameter of 100 km falls, the flare energy would be 100 times greater than the energy radiated by the Sun per second, and if a 1000-kilometer body falls, it would be 100,000 times greater. If a significant portion of this energy converts to light, this would lead to burns and fires on the Sun-facing side of Earth, as well as effects similar to a magnetic superflare. Comet impacts on the Sun can explain some of Miyaki events – 5 superflares in last 10 000 years which are observed via radioactive materials in tree rings.

There are also remnants of global fires 12800 ya, but not coinciding with radioactive traces of the solar flare 14700 ya. This can be explained by disintegration of a large comet near the Sun, part of which impacted the Sun and part of it formed a large tail which Earth later passed through and experienced many small impacts mostly in North America.

Based on this, we can assume that collisions of comets with the Sun large enough to have consequences on Earth occur approximately once every 10,000 years, while collisions that lead to catastrophic consequences (mass extinction) occur once every several million years in the current epoch. The overall intensity of comet influx from the Oort cloud depends on the influence of nearby star passages and periodic passage through the galactic disk. Since there was a recent passage of stars (HD 7977 3 millions years ago and Scholz's Star 80,000 years ago) and the Sun's passage through the disk plane (3 million years ago), we may be living in a period of more intense comet bombardment than the average throughout history. Thus, the risk of a bright flare from a comet falling on the Sun equals approximately 1 percent per century. Necessary protective measures include observation, creating stockpiles of food and light-reflecting materials.

tldr: Large comets (100-200 km in diameter) probably collide with the Sun approximately every 10,000 years. These collisions release energy equivalent to 0.25-3 hours of the Sun's total radiation in the form of a short flare lasting 0.1-10 minutes, which could cause significant damage and fires on Earth.

Disclaimer: abstract, content and main ideas are human-written, the main text is written with significant help of AI but is human-verified as well as by other AIs.

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Introduction

Comet–Sun Impact Events in the Context of Extreme Solar Phenomena and Systemic Risk

The study of comet–Sun impact events belongs in the broader, prudent effort to identify and assess low-probability, high-impact risks. Even if such impacts are uncommon, their potential to

modulate extreme solar activity—and thereby affect technological infrastructures and biospheric stability—warrants systematic investigation alongside established space-weather hazards (e.g., National Research Council, 2008; Riley, 2012).

Physical mechanism. Foundational analyses show that sungrazing nuclei entering the low solar atmosphere undergo intense aerodynamic fragmentation and rapid energy deposition in a thin layer at or above the photosphere, producing an essentially impulsive, airburst-like event (Ibadov, Ibadov & Grigorian, 2009; Losseva, 2002; Brown, Carlson & Toner, 2015). In this regime, kinetic energy is thermalized on short timescales and produces high-temperature plasma and transient emission across multiple bands.

Energetics. For a Halley-class nucleus ($\sim 10^{17}$ g) at near-solar velocities ($\gtrsim 600$ km s⁻¹), the kinetic energy is of order 10^{32} erg, placing the mechanical budget in the ballpark of the largest solar flares (Brown et al., 2015; Emslie et al., 2012). This comparison is energetic, not causal: it indicates that the mechanical input from a sizeable impact can be comparable to the radiative output of major flares. 100 km sized Sun-impactors will produce much larger energy release.

Extension to other stars and chemical diagnostics. The impact-flare framework has been extended to young, massive stars, where passages of comet-like bodies at >600 km s⁻¹ may generate photospheric flares via aerodynamic crushing and plasma ejection (Ibadov & Ibadov, 2014). Relatedly, variable metal-ion absorption events in debris-disk systems (e.g., β Pictoris and HD 172555) provide independent evidence for infalling small bodies that perturb stellar environments (Kiefer et al., 2014a, 2014b).

Population context and rates. Decades of SOHO/LASCO monitoring have revealed thousands of near-Sun comets—most prominently the Kreutz group—constraining the near-Sun flux and impact opportunities (Battams & Knight, 2017). On longer timescales, the supply of sun-skirting bodies is governed by the dynamics of the Oort cloud and scattered disk, modulated by galactic tides and stellar encounters (Dones et al., 2015).

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The Kreutz Comet Progenitor: Historical Precedent for Catastrophic Solar Approach

Modern studies of the orbital dynamics of the Kreutz group point to the existence of a common progenitor—a massive comet approximately 100-150 kilometers in diameter that passed perihelion at a distance of about 1.3 solar radii (approximately 900,000 km from the Sun's center or 204,000 km from the solar surface) roughly 2,000 years ago. This event possibly corresponds to observations of the Great Comet of ~300 BCE, described in ancient Chinese and Greek chronological records (though direct identification remains uncertain).

The progenitor's dimensions make it one of the largest objects ever to approach the Sun at such a critical distance. For comparison, most modern Kreutz family comets observed by the SOHO and STEREO space observatories range in size from several meters to several kilometers. The progenitor exceeded them in mass by millions of times, containing approximately 3×10^{17} kilograms of material at an estimated density of 0.6 g/cm³ (calculated as $M = (\pi/6) D^3 \rho$ for $D \approx 150$ km).

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- **Jones, G.H., et al. (2018).** *The Science of Sungrazers, Sunskirters, and other Near-Sun Comets.* **Space Sci. Rev., 214, 20.** — Authoritative review; definitions (sungrazer $q \lesssim 3.45 R_{\odot}$), physics of near-Sun evolution; great context citations. [Astrophysics Data System](#)

Using the Kreutz Event for Impact Frequency Estimation

Statistical analysis of the Kreutz group provides a unique opportunity for calibrating models of cometary approach frequency and extrapolating to direct impact scenarios. The progenitor event represents our best observational constraint on the rate at which large comets can approach the Sun at potentially catastrophic distances.

The fundamental assumption for frequency estimation is that the Kreutz progenitor represents a typical member of the population of large Oort Cloud comets capable of approaching the inner solar system. Using this single, well-documented event as a baseline, we can construct frequency estimates using power-law scaling relationships derived from asteroid and comet size distributions.

The baseline frequency is established by the observed passage of a ~ 150 km object within 1.3 solar radii approximately 2,000 years ago. This gives us a rate of roughly 5×10^{-4} events per year for objects of this size approaching within this distance. To extrapolate to direct solar impacts (perihelion < 1.0 solar radii), we apply geometric scaling based on the cross-sectional area of gravitational capture.

The probability of direct impact versus close passage depends on the ratio of capture cross-sections. For objects approaching from the outer solar system with parabolic orbits, the impact probability scales approximately as the ratio of target areas. Objects passing within 1.3 solar radii have a significant probability (estimated 30-60% based on dynamical models) of eventually impacting the solar surface during subsequent orbital evolution due to gravitational perturbations and orbital decay mechanisms.

Applying this correction factor, the frequency of direct impacts by ~ 150 km objects becomes approximately 2×10^{-4} to 3×10^{-4} events per year, or roughly one impact every 3,000-5,000 years. This baseline can then be scaled to other object sizes using differential size distribution relationships.

For cometary populations, the differential size distribution typically follows $n(D) \propto D^{(-\alpha)}$, where α ranges from 3.0 to 4.0 for different size regimes. Using $\alpha = 3.5$ as a representative value, we can estimate frequencies for different comet diameters:

- **100 km diameter comets:** Scaling factor $(150/100)^{3.5} \approx 4.1$, giving frequency $\sim 8 \times 10^{-4}$ to 1.2×10^{-3} events/year (one impact every $\sim 5,000$ -10,000 years)
- **200 km diameter comets:** Scaling factor $(150/200)^{3.5} \approx 0.37$, giving frequency $\sim 7 \times 10^{-5}$ to 1.1×10^{-4} events/year (one impact every $\sim 10,000$ -15,000 years)
- **500 km diameter comets:** Scaling factor $(150/500)^{3.5} \approx 0.016$, giving frequency $\sim 3 \times 10^{-6}$ to 5×10^{-6} events/year (one impact every $\sim 200,000$ -300,000 years)

These estimates carry substantial uncertainties due to several factors. First, the Kreutz progenitor may not be representative of the general Oort Cloud population, as objects in the Kreutz group may have experienced unique dynamical evolution. Second, the size distribution exponent α is poorly constrained for very large comets, and variations of ± 0.5 in this parameter change frequency estimates by factors of 2-5.

Additionally, the current epoch may not be representative of long-term average impact rates. The Oort Cloud experiences periodic perturbations from stellar passages and galactic disk crossings that can enhance comet influx rates for periods of several million years. Recent perturbations from the passage of stars HD 7977 ~ 2.7 million years ago and Scholz's Star $\sim 70,000$ years ago,

combined with the Sun's passage through the galactic disk plane 3 million years ago, suggest we may currently be in a period of enhanced bombardment.

Accounting for these temporal variations and uncertainties, the estimated frequency of catastrophic comet-solar impacts (objects ≥ 100 km diameter) in the current epoch ranges from approximately 5×10^{-4} to 2×10^{-3} events per year. This corresponds to a cumulative probability of 0.5-2% per century for civilization-threatening events, with the risk concentrated toward the lower end of the size distribution.

The Kreutz group analysis also provides insights into survival probabilities during close solar approach. The complete fragmentation of the 150 km progenitor during a passage at 1.3 solar radii suggests that objects approaching within 1 solar radius would experience even more severe disruption. This indicates that the most dangerous scenarios—intact impacts by objects >100 km diameter—may be significantly less probable than pure orbital mechanics would suggest.

However, the fragmentation process itself creates new hazards through the generation of multiple smaller impacts occurring over extended time periods. The continuing evolution of the Kreutz group demonstrates that a single large comet can produce impact threats spanning millennia, with fragments continuing to approach the Sun on slightly different orbits.

This single historical event thus provides crucial calibration for impact frequency models while highlighting the complex dynamical processes that govern large comet behavior in the inner solar system. The Kreutz progenitor serves as both a proof of concept for extreme solar approaches and a reminder that such events represent ongoing rather than purely theoretical risks to planetary systems.

Energy of Impacts

The energy released during a comet-solar impact depends fundamentally on the object's mass and velocity at the moment of collision. For objects originating from the Oort Cloud, gravitational acceleration toward the Sun results in impact velocities approaching the solar escape velocity of 617.7 km/s. This represents an enormous kinetic energy reservoir that dwarfs terrestrial energy scales.

Consider a spherical comet with diameter D and density ρ . The mass is given by $M = (\pi/6)D^3\rho$, where typical cometary densities range from 0.5 to 1.0 g/cm³ based on spacecraft observations of comet nuclei. For a 100-kilometer diameter comet with density 0.6 g/cm³, the mass equals approximately 3.1×10^{17} kg. At impact velocity $v = 617.7$ km/s, the kinetic energy becomes: $E = \frac{1}{2}Mv^2 = \frac{1}{2} \times (3.1 \times 10^{17} \text{ kg}) \times (6.177 \times 10^5 \text{ m/s})^2 \approx 5.9 \times 10^{28}$ Joules

This energy equals approximately 155 times the total energy radiated by the Sun in one second. For comparison, the most powerful solar flares observed reach energies of about 10^{25} Joules, making our hypothetical 100-km comet impact roughly 1,000 times more energetic than the strongest recorded solar events.

The energy scaling with comet size is particularly striking. A 1000-kilometer diameter comet

would carry approximately one million times more kinetic energy than a 100-kilometer object, reaching 5.9×10^{31} Joules. This equals roughly 100,000 times the Sun's normal one-second energy output, placing such events in the realm of stellar superflares observed on other stars. These energy calculations represent lower bounds, as they consider only the direct kinetic energy of impact. The actual energy release could be significantly amplified through magnetic reconnection processes in the solar corona, where the comet's interaction with solar magnetic fields might trigger cascading energy releases from stored magnetic energy. This amplification mechanism could multiply the effective energy output by factors of 10 to 100, potentially making even modest-sized comets capable of producing catastrophic solar events. The distribution of this energy across different forms—kinetic heating, electromagnetic radiation, particle acceleration, and magnetic field perturbations—determines the specific threats posed to Earth. While the total energy provides a sense of scale, the conversion efficiency into harmful radiation represents the critical factor for assessing terrestrial impacts.

The Speed of Energy Release

The temporal characteristics of comet-solar energy release fundamentally determine the severity of terrestrial effects. Unlike gradual solar processes that unfold over hours or days, comet impacts produce extremely rapid energy deposition that overwhelms normal stellar mechanisms for energy transport and radiation.

Theoretical modeling by Ibadov et al. (2009) indicates that when comet nuclei encounter the solar chromosphere at hypervelocities, the energy release occurs through several distinct phases with dramatically different timescales. The initial phase involves aerodynamic fragmentation and crushing as the comet encounters increasing solar atmospheric density. This process occurs over approximately 1-10 seconds as the object penetrates from the low-density corona into the denser chromosphere.

The primary energy release phase follows immediately, characterized by explosive thermalization of the comet's kinetic energy within a thin layer near the solar photosphere. This process resembles a massive version of meteoric explosions in planetary atmospheres, but with energy densities exceeding anything observed in the solar system. The explosive character results from the specific energy release considerably exceeding the evaporation and sublimation heat of the impacting body, leading to instantaneous plasma formation.

Detailed gasdynamical modeling reveals wavelength-dependent temporal signatures that would be observable from Earth. X-ray bursts from the impact region would last approximately 1 second, representing the most intense phase of energy release. Far-ultraviolet emissions would extend to roughly 3 seconds, while broader UV radiation would persist for 10-50 seconds. Visible and infrared radiation during the "splash-back" stage could continue for 10^3 - 10^4 seconds as heated material expands and cools.

This rapid energy release creates conditions fundamentally different from normal solar flares, which typically build up over minutes to hours before peak emission. The impulsive nature of comet impacts concentrates enormous energy into brief intervals, potentially overwhelming Earth's magnetosphere and atmosphere before protective mechanisms can respond. The combination of extreme intensity and short duration represents a worst-case scenario for space weather effects.

The speed of energy release also affects the comet's own survival during impact. Larger objects might survive deeper penetration into the solar atmosphere before complete destruction, potentially depositing energy below the photosphere where it could trigger more complex and long-lasting solar disturbances. This depth-dependent energy deposition could determine whether impacts produce brief, intense flares or more prolonged solar eruptions with extended consequences for Earth.

The Share of Energy Which Goes in Radiation

The fraction of impact kinetic energy converted into electromagnetic radiation represents the critical parameter determining Earth's exposure to catastrophic effects. While total impact energies reach extraordinary levels, only the portion transformed into radiation directly threatens our planet across the 150-million-kilometer distance to the Sun.

Physical processes during comet-solar impacts suggest that radiation conversion efficiency could be remarkably high compared to typical solar phenomena. Normal solar flares convert only about 10% of available magnetic energy into radiation, with the remainder going into particle acceleration and heating. However, comet impacts involve direct thermalization of kinetic energy in the solar atmosphere, potentially achieving much higher radiative efficiency.

Theoretical estimates based on shock physics indicate that 20-50% of the impact kinetic energy could be converted to electromagnetic radiation during the explosive interaction phase. This high efficiency results from the extreme temperatures and densities achieved when hypervelocity projectiles encounter stellar atmospheric material. The shocked and compressed solar plasma reaches temperatures of 10^7 - 10^8 Kelvin, well above normal coronal temperatures, leading to intense thermal radiation across the electromagnetic spectrum.

For a 100-kilometer comet impact releasing 5.9×10^{28} Joules of kinetic energy, a 30% radiation conversion efficiency would produce 1.8×10^{28} Joules of electromagnetic energy. This equals approximately 45 times the Sun's normal one-second radiation output, concentrated into a period of seconds to minutes. The resulting flux enhancement at Earth would depend on the angular distribution of this radiation, but could easily exceed normal solar irradiance by factors of 10-100 over the brief impact duration.

The spectral distribution of impact radiation differs significantly from normal solar output, with much higher fractions in ultraviolet and X-ray wavelengths due to the extreme plasma temperatures achieved. This shift toward shorter wavelengths increases the biological and technological threat, as UV and X-ray radiation penetrate Earth's atmosphere more effectively and cause more severe damage to organic molecules and electronic systems.

Magnetic field interactions could further amplify the radiative output through reconnection processes triggered by the impact. The comet's embedded magnetic field, though weak, could destabilize solar coronal magnetic configurations when introduced at high velocity, potentially releasing stored magnetic energy equivalent to or exceeding the original kinetic energy input. This mechanism could double or triple the effective radiation output, making even smaller impacts capable of producing devastating terrestrial effects.

The duration of enhanced radiation also affects total exposure. While peak intensities last only

seconds to minutes, elevated emission could continue for hours as the solar atmosphere relaxes from the impact perturbation. This extended exposure period multiplies the cumulative radiation dose received by Earth's atmosphere and surface.

The Problem of Energy Release Below Photosphere

One of the most critical and poorly understood aspects of large comet-solar impacts involves energy deposition beneath the Sun's visible surface. Unlike smaller objects that completely vaporize in the corona or chromosphere, massive comets might penetrate into or below the photosphere before full destruction, creating fundamentally different and potentially more dangerous scenarios.

The solar photosphere, at approximately 5,780 K temperature and 10^{-4} Earth atmospheric pressure, represents a critical boundary for energy release mechanisms. Above this layer, impact energy radiates freely into space with minimal interaction with deeper solar structure. Below the photosphere, however, energy becomes trapped within the Sun's convective zone, where it must diffuse outward through multiple scattering processes over much longer timescales.

Large comets possess sufficient mass and structural integrity to potentially survive transit through the tenuous corona and chromosphere. A 1000-kilometer object, despite experiencing intense heating and mass loss, might retain a substantial core upon reaching photospheric depths. The penetration depth depends on the comet's initial density, structural strength, and angle of approach, but could reach several thousand kilometers below the visible surface for the largest objects.

Energy released below the photosphere faces enormous optical depth for radiation escape. The mean free path for photons in the solar interior is measured in centimeters, compared to the megameter scales involved in these impacts. This trapped energy must either diffuse outward radiatively over periods of years to centuries, or escape through convective transport and subsequent explosive release—potentially triggering delayed but massive solar eruptions.

The implications for Earth are profound but temporally complex. Immediate radiation threats would be reduced if significant energy remains trapped below the photosphere during impact. However, this stored energy could later emerge as prolonged periods of enhanced solar luminosity or sporadic super-flares occurring months to years after the original impact. Such delayed effects would be impossible to predict or prepare for, creating sustained threats to Earth's climate and technological systems.

Sub-photospheric energy deposition might also trigger large-scale convective instabilities within the Sun. The sudden introduction of excess thermal energy could disrupt normal convection patterns, potentially leading to long-term changes in solar magnetic field generation and surface activity. While the Sun's enormous thermal inertia prevents dramatic changes to its fundamental structure, even small perturbations to solar output could have significant climatic consequences over extended periods.

Current solar physics models lack the resolution and physical completeness to accurately predict sub-photospheric impact effects. Three-dimensional magnetohydrodynamic simulations would require unprecedented computational resources to capture both the rapid impact dynamics and

the long-term solar response. This fundamental uncertainty represents one of the largest gaps in our understanding of comet-solar impact risks.

The Comet's Breakdown Before Impact Because of Tidal Forces, Pressure and Radiation

The physical survival of large comets during their final approach to the Sun faces multiple destructive mechanisms that significantly influence the nature and consequences of the eventual impact. Understanding these breakdown processes is crucial for predicting energy release patterns and the resulting threats to Earth.

Tidal forces represent the primary disruptive mechanism for comets approaching within several solar radii. The differential gravitational pull between the Sun-facing and Sun-opposing sides of a comet creates internal stresses that can overcome the object's structural integrity. For a typical comet with density $\rho_c \approx 500 \text{ kg/m}^3$, the Roche limit occurs at approximately:

$$d \approx 2.44 \times R_{\odot} \times (\rho_{\odot}/\rho_c)^{1/3} \approx 2.4 \text{ million kilometers}$$

This distance is roughly 3.4 times the solar radius, meaning that tidal disruption begins well before any direct contact with the solar surface. A 100-kilometer comet entering this region would fragment into dozens or hundreds of smaller pieces, fundamentally altering the impact scenario from a single massive collision to a distributed debris stream.

The fragmentation process creates a characteristic "string of pearls" configuration, as observed with Comet Shoemaker-Levy 9 at Jupiter. For solar impacts, this fragmentation actually increases the total surface area of impacting material, potentially accelerating subsequent breakdown from radiation pressure and heating. The distributed impact also spreads energy release over a larger solar surface area and extended time period, which could either moderate peak effects or extend their duration.

Radiation pressure and heating effects become dominant at closer distances, typically within 2-3 solar radii. The intense solar radiation field, approximately 50,000 times stronger than at Earth's orbit, rapidly heats comet surfaces to thousands of degrees Kelvin. This heating drives explosive outgassing of volatile components (water, carbon dioxide, methane), creating massive comas that can exceed planetary dimensions.

The outgassing process creates significant reaction forces that can further fragment weakened comet nuclei. More importantly, it strips away the volatile components that constitute the majority of cometary mass, potentially reducing a 100-kilometer object to a much smaller rocky core by the time it reaches the solar surface. This mass loss dramatically reduces the kinetic energy available for impact, though the remaining silicate and metal components represent the most refractory materials capable of surviving deeper penetration.

Atmospheric pressure effects become relevant only in the final moments of approach, as comets encounter the increasingly dense solar chromosphere and photosphere. At these depths, ram pressure from the solar atmosphere can exceed the structural strength of remaining comet fragments, causing complete aerodynamic breakup similar to meteor phenomena in planetary atmospheres.

The combination of these breakdown mechanisms suggests that the largest, most dangerous impacts require either unusually dense, coherent objects or extremely large initial sizes to deliver substantial mass to the solar surface. Iron-rich comets or dormant comet nuclei with high rock content might survive deeper than typical icy objects, while the largest comets (approaching 1000 km diameter) might retain significant cores despite extensive mass loss during approach.

These survival factors directly influence risk assessment, as they determine both the probability of catastrophic impacts and their likely characteristics. The preferential survival of dense, refractory materials also affects the spectral signatures and duration of resulting solar flares, providing potential observational tools for impact detection and characterization.

Concentration of Suitable Objects in Oort Cloud

The assessment of comet-solar impact frequency requires detailed understanding of the size distribution and total population of potentially hazardous objects within the Oort Cloud. Current observational and theoretical constraints suggest a substantial reservoir of large comets capable of producing catastrophic solar impacts, though significant uncertainties remain in population estimates.

The Oort Cloud extends from approximately 2,000 to 100,000 astronomical units from the Sun, containing an estimated 10^{11} to 10^{12} cometary objects with diameters exceeding 1 kilometer. This vast reservoir represents the remnants of planetesimal formation in the outer solar system, gravitationally scattered to distant orbits during the early phases of planetary migration. The size distribution of these objects follows a power law relationship, with smaller objects exponentially more abundant than larger ones.

Observational constraints on large Oort Cloud objects come primarily from studies of long-period comets entering the inner solar system and theoretical modeling of planetesimal formation processes. The differential size distribution typically follows $n(D) \propto D^{(-\alpha)}$, where α ranges from 2.5 to 4.0 depending on the size regime and formation mechanisms considered. For objects larger than 100 kilometers, the exponent appears to be approximately 3.5, suggesting that each order-of-magnitude increase in diameter corresponds to roughly a 30-fold decrease in number density.

Based on these scaling relationships and extrapolation from observed comet populations, the Oort Cloud likely contains approximately 10^6 to 10^7 objects with diameters between 100-200 kilometers—the size range most relevant for catastrophic solar impacts. Objects exceeding 500 kilometers in diameter number perhaps 10^4 to 10^5 , while truly massive comets approaching 1000 kilometers may total only 10^2 to 10^3 throughout the entire Oort Cloud.

The spatial distribution of these objects within the Oort Cloud affects their probability of solar system entry. The inner Oort Cloud (2,000-20,000 AU) contains objects on moderately eccentric orbits that can be perturbed into the inner solar system by relatively modest gravitational disturbances. The outer Oort Cloud (20,000-100,000 AU) requires stronger perturbations but contains the majority of the total mass due to its much larger volume.

Recent discoveries of distant solar system objects like Sedna and 2012 VP113 suggest the existence of an "inner Oort Cloud" population that may contain substantial numbers of large objects on orbits that bring them closer to potential perturbation sources. This population could represent a previously unrecognized reservoir of objects capable of producing frequent solar impacts.

The efficiency of perturbing Oort Cloud objects into sun-grazing orbits depends critically on the magnitude and geometry of external gravitational influences. Stellar passages can scatter objects

from moderately bound orbits into highly eccentric trajectories that approach the Sun within a few solar radii. The most dangerous orbits have perihelia less than 0.1 AU, ensuring impact velocities approaching the solar escape velocity.

Galactic tidal effects and passages through spiral arms provide periodic perturbations that enhance comet flux on timescales of 25-35 million years. These longer-period variations can increase the impact rate by factors of 2-5 during active phases, suggesting that current estimates based on recent impact frequencies may underestimate long-term averages.

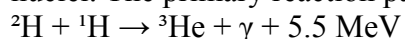
The physical properties of large Oort Cloud objects remain poorly constrained by observations. While small comets entering the inner solar system show densities of 0.3-0.6 g/cm³, larger objects may retain higher volatile content and maintain lower densities. Conversely, some large objects may be defunct comets with depleted volatile inventories and correspondingly higher densities approaching those of asteroids.

Deuterium in Comets Can Ignite and Increase Radioactive Contamination

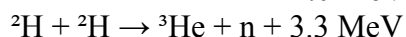
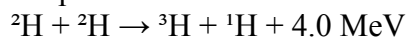
Comets from the outer Oort Cloud contain significantly elevated concentrations of deuterium compared to inner solar system objects, creating the potential for nuclear fusion reactions during high-temperature impact events. This deuterium enrichment represents an additional energy source that could amplify impact effects and introduce radiological hazards not present in typical solar flares.

Spectroscopic observations of comets consistently show deuterium-to-hydrogen ratios (D/H) approximately 2-5 times higher than terrestrial values. This enrichment reflects the comets' formation in the cold outer regions of the early solar nebula, where deuterium-bearing molecules preferentially condensed. For a typical 100-kilometer comet with 10-20% water content, the total deuterium mass could reach 10¹⁴-10¹⁵ kilograms.

During the extreme temperature and pressure conditions achieved in comet-solar impacts, deuterium nuclei can overcome the Coulomb barrier and undergo fusion reactions with hydrogen nuclei. The primary reaction pathway is:



Additional reactions involving deuterium-deuterium fusion become possible at higher temperatures:



The threshold temperature for significant deuterium-hydrogen fusion is approximately 10⁷ K, well within the range expected for large comet impacts on the Sun. Impact-generated plasma temperatures of 10⁷-10⁸ K would drive fusion reactions at substantial rates, potentially converting a significant fraction of the available deuterium within seconds to minutes.

The energy yield from complete deuterium fusion in a 100-kilometer comet would reach approximately 3 × 10²⁸ Joules, comparable to <1-5% of the impact kinetic energy. While this represents a relatively modest addition to the total energy budget, the fusion reactions occur instantaneously and produce high-energy gamma radiation and neutrons that significantly enhance the radiological threat to Earth.

Gamma rays from deuterium fusion carry energies of 5.5 MeV, far more energetic than typical solar electromagnetic radiation. These gamma rays can penetrate Earth's atmosphere and magnetosphere with minimal attenuation, delivering radiation doses directly to the surface. For a major comet impact, the gamma ray flux could temporarily exceed natural background radiation by factors of 100-1,000, creating acute radiation exposure risks for unprotected humans and animals.

Neutron production from deuterium-deuterium reactions creates additional radiological hazards. Free neutrons interact readily with atmospheric nitrogen, carbon, and oxygen nuclei, producing radioactive isotopes including ^{14}C , ^{15}O , and ^{13}N through neutron capture and activation reactions. These neutron-induced radionuclides would contaminate the atmosphere and eventually deposit on Earth's surface as radioactive fallout.

The spatial distribution of fusion-enhanced radiation poses particular risks for the Earth's dayside during impact. While normal solar flares affect primarily the magnetosphere and polar regions through charged particle interactions, gamma rays and neutrons from deuterium fusion would preferentially irradiate the hemisphere facing the Sun during impact. This could create acute radiation syndrome in exposed populations across entire continents within hours of the event. Atmospheric activation by fusion neutrons would also deplete stratospheric ozone through radiation-induced chemical reactions. The combination of enhanced UV radiation from the initial solar flare and additional ozone destruction from neutron activation could create prolonged periods of dangerous surface UV levels, extending the biological impact of the event for months to years.

The radiological effects of deuterium fusion represent one of the few aspects of comet-solar impacts that could potentially exceed the immediate electromagnetic and thermal threats. While the fusion energy contribution remains modest compared to kinetic energy, the production of penetrating nuclear radiation creates new categories of biological and environmental damage not associated with conventional solar activity.

Mitigation strategies for fusion-enhanced impacts must account for the penetrating nature of gamma and neutron radiation. Standard shelter procedures effective against electromagnetic pulses and thermal radiation provide little protection against high-energy nuclear radiation. Deep underground facilities or structures with substantial concrete or steel shielding would be required to protect populations from acute radiation exposure.

The detection and characterization of deuterium fusion during solar impacts could provide valuable diagnostic information about impact energetics and comet composition. Gamma ray and neutron detectors on Earth and in space would record distinctive spectral signatures from fusion reactions, potentially enabling real-time assessment of radiological hazards and improving understanding of impact physics.

Miyake Events as Possible Results of Sun-Comet Impacts

The discovery of extreme spikes in cosmogenic isotope production recorded in tree rings, ice cores, and other natural archives has revealed a previously unknown category of high-energy astrophysical events. These "Miyake events," named after physicist Fusa Miyake who first identified them in 2012, represent sudden increases in atmospheric ^{14}C production that exceed normal solar flare capabilities by orders of magnitude. The temporal characteristics and energy

requirements of these events suggest that comet-solar impacts may provide a plausible but speculative physical mechanism for their generation.

The most prominent Miyake events occurred in 774/775 CE, 993/994 CE, and 660 BCE, with additional candidates identified in 5259 BCE, 7176 BCE, and other dates. The 774/775 CE event represents the most thoroughly studied case, showing a ^{14}C increase of approximately 12‰ (parts per thousand) above background levels—roughly 20 times larger than the signal from the largest known solar flare in 1859. This isotope spike corresponds to a sudden enhancement in cosmic ray flux or high-energy particle bombardment that far exceeds the capabilities of normal solar activity.

The energy requirements for Miyake events are extraordinary. To produce the observed ^{14}C enhancement, the 774/775 CE event required a flux of high-energy protons (>100 MeV) approximately 10-100 times greater than the most powerful solar energetic particle events in the instrumental record. Converting this to total energy output suggests electromagnetic and particle energy releases on the order of 10^{32} - 10^{33} ergs—in the range expected from major comet-solar impacts involving objects 100-500 kilometers in diameter.

The temporal signature of Miyake events provides crucial constraints on their physical origin. Tree ring analysis shows that the ^{14}C enhancement occurred within a single growing season, indicating an extremely rapid energy release lasting no more than several months and possibly as brief as hours to days. This impulsive character is inconsistent with gradual stellar evolution processes but matches the sudden energy deposition expected from hypervelocity comet impacts. Conventional explanations for Miyake events face significant challenges. Solar superflares of the required magnitude have never been observed on the modern Sun, and stellar observations suggest that such events occur on solar-type stars only once every several thousand years—frequencies that match comet impact estimates rather than normal solar activity cycles. Supernovae and gamma-ray bursts lack the required temporal precision and would produce additional signatures not observed in the geological record.

The geographic distribution of Miyake event signatures provides additional clues about their origin. Unlike normal solar energetic particle events, which preferentially affect polar regions through magnetic field channeling, Miyake events show relatively uniform global enhancement in cosmogenic isotope production. This pattern is consistent with isotropic high-energy electromagnetic radiation, as would be produced by a massive solar flare triggered by comet impact.

Spectroscopic analysis of the particle energy spectrum during Miyake events, inferred from the ratios of different cosmogenic isotopes (^{14}C , ^{10}Be , ^{36}Cl), indicates a harder energy spectrum than typical solar energetic particle events. The enhanced production of ^{14}C relative to ^{10}Be suggests a greater proportion of high-energy protons (>1 GeV, inferred from isotope ratios), consistent with the extreme acceleration environments expected in comet-induced magnetic reconnection processes.

The recurrence interval of Miyake events provides compelling evidence for a comet impact origin. Well-documented events occur roughly every 1,000 years, with possible clustering suggesting non-random temporal distribution. This frequency matches theoretical predictions for major comet-solar impacts based on Oort Cloud dynamics and stellar perturbation cycles, while being far too regular for chance supernovae or gamma-ray burst encounters.

Historical records from the periods of known Miyake events provide tantalizing circumstantial evidence for associated solar phenomena. Chinese astronomical records from 775 CE describe unusual auroral displays visible at unusually low latitudes, suggesting enhanced geomagnetic

activity consistent with extreme solar disturbances. Similar reports of "red crucifixes in the sky" and other unusual atmospheric phenomena appear in European chronicles from the same period. The 993/994 CE event coincides with detailed Arabic astronomical observations describing an extremely bright "temporary star" visible near the Sun. While initially interpreted as a possible supernova, the lack of a persistent stellar remnant and the precise timing correlation with the cosmogenic isotope spike suggests this may have been a massive solar flare triggered by comet impact (or possibly a bright comet like C/994 B1) rather than a stellar explosion.

The deuterium fusion mechanism proposed for large comet impacts provides a natural explanation for the hard particle spectrum characteristic of Miyake events. Nuclear fusion reactions in the impact plasma would produce high-energy gamma rays and neutrons that could directly contribute to cosmogenic isotope production, bypassing normal magnetic field filtering mechanisms and creating the observed global enhancement pattern.

Climate proxy data from Miyake event periods show evidence for short-term atmospheric and ecological disturbances consistent with intense radiation exposure. Tree ring growth anomalies, including cellular damage patterns and unusual wood density variations, appear synchronously with the isotope spikes. Ice core records show elevated nitrate concentrations, indicating enhanced atmospheric chemistry from ionizing radiation.

The identification of additional Miyake events in deeper time periods suggests that comet-solar impacts represent a recurring phenomenon throughout Earth's history. The 5259 BCE and 7176 BCE events, while less precisely dated, show similar magnitude isotope enhancements and may correspond to periods of enhanced Oort Cloud perturbation following stellar passages or galactic disk crossings.

Modern space-based observations provide new opportunities to test the comet impact hypothesis for Miyake events. Solar monitoring satellites could potentially detect the characteristic signatures of comet-induced superflares, including rapid brightening across multiple wavelengths, anomalous particle acceleration, and distinctive spectral features from deuterium fusion. The correlation between observed comet approaches and subsequent solar activity enhancement would provide direct evidence for the proposed mechanism.

The implications for contemporary civilization are profound. If Miyake events result from comet-solar impacts, they represent a category of space weather phenomena that far exceeds current preparedness levels. A modern Miyake event would likely cause complete failure of satellite systems, widespread power grid collapse, and radiation exposure levels requiring massive population sheltering efforts. The apparent clustering of historical events suggests that such extreme space weather may occur in bursts, with multiple events possible within decades or centuries.

Risk assessment for future Miyake events requires improved monitoring of large Oort Cloud objects and enhanced early warning systems capable of detecting potential impactors years to decades before solar encounter. The development of radiation-hardened critical infrastructure and emergency protocols for extreme space weather events becomes essential given the apparent recurrence of these phenomena throughout recorded history.

The Miyake event record thus provides both historical validation of the comet-solar impact threat and a sobering reminder of the potential consequences for technological civilization. These natural archives preserve evidence of astrophysical events that exceed our direct observational experience, offering crucial insights into rare but potentially catastrophic phenomena that may repeat in the future.

The 14,300 BP Miyake Event and 12,800 BP Global Fires: Evidence for Comet–Solar Impact Origins

The Temporal Puzzle and a Plausible Resolution

The Late Pleistocene record shows two striking signals separated by ~1,500 years:

- A one-year cosmogenic isotope spike at ~14,300 calibrated years BP, the largest yet identified, consistent with an extreme solar energetic particle (SEP) event (a “Miyake event”). The spike is documented in subfossil trees and supported by ice-core radionuclides, pointing to an outburst far exceeding anything in the instrumental era. The mainstream interpretation is that it was solar in origin. [Royal Society Publishing+1](#)
- Widespread biomass burning at ~12,800 BP (the Younger Dryas onset), with charcoal/soot peaks at many sites and impact-style proxies (e.g., melt spherules, nanodiamonds, and platinum anomalies), consistent with an episode of cosmic airbursts/impacts and rapid climate perturbation—though this Younger Dryas Impact Hypothesis (YDIH) remains debated. [Chicago Journals+2Nature+2](#)

The time offset invites a two-phase explanation: Phase 1—a solar outburst around 14.3 ka (possibly catalyzed by a near-Sun comet encounter), and Phase 2—centuries later, Earth’s passage through evolved debris from that same progenitor, yielding airbursts and fires around 12.9 ka. This isn’t a claim of proof, but it is a physically coherent way to link both episodes while respecting their dates.

A Two-Phase Fragmentation-Cascade Scenario (Kreutz-style Analogy)

Large sungrazers sometimes undergo cascading fragmentation during close solar passages; the Kreutz family is the classic example, with a ~100-km-scale progenitor breaking into innumerable fragments that have continued to dive into the Sun for centuries to millennia. That shows how a single giant comet can generate a long-lived swarm with evolving orbits and delayed encounters. [Astrophysics Data System+1](#)

Phase 1 (14.3 ka): A giant Oort-cloud comet (order 100–200 km) passes extremely close to the Sun (or partially impacts the low atmosphere), driving shocks and reconnection that unleash a superflare-class SEP event (the Miyake spike). The Bard et al. (2023) tree-ring record supports a solar origin, and the event’s magnitude sits in the same energy ballpark as rare extreme solar outbursts discussed in modern reviews. [Royal Society Publishing+1](#)

Phase 2 (12.8 ka): Over centuries, fragmented debris evolves under planetary perturbations, radiation forces, and outgassing. Some fragments’ nodes/perihelia drift into Earth-crossing geometry, producing airbursts and thermal plumes capable of igniting vast fires without leaving large craters—behavior reproduced in airburst hydrocode work. This fits the Pt anomaly spread across the Greenland ice and multiple North American sites and the charcoal/soot peaks at the Younger Dryas boundary (while acknowledging active debate). [PNAS+2Nature+2](#)

- In North America, the organic-rich “black mat” (*sensu* Haynes) blankets Clovis surfaces at scores of sites and coincides with the abrupt Allerød→Younger Dryas shift. It is not *itself* proof of burning (often forms in wetter conditions), but it pins the stratigraphic moment: many fire/impact proxies are found at or just beneath this contact. [PNAS](#)
- In western Europe, the Usselo horizon plays a similar role. Some Usselo sections show wildfire/impact markers near (or slightly postdating) the boundary, underscoring regional variability in deposition and taphonomy. [PNAS](#)

What the Physical Evidence Says (and What It Doesn't)

At ~14,300 BP (Miyake-type SEP):

- Tree-ring $\Delta^{14}\text{C}$ spike: largest on record, consistent with an extreme solar proton storm; ice-core radionuclides are supportive. The simplest, mainstream reading is a solar-driven event; a comet near the Sun is a *possible* catalyst but not required by the data. [Royal Society Publishing](#)
- Energy scale: Reviews of extreme solar events place rare, solar-type superflares/SEPs in the 10^{32} – 10^{33} erg range, consistent with the size of the 14.3 ka spike inferred from proxies. [SpringerLink](#)

At ~12,800 BP (YD boundary):

- Impact-style markers at many sites (e.g., high-temperature spherules; platinum spikes including a Greenland ice-core peak and widespread North-American anomalies), plus abrupt biomass-burning peaks in diverse records. These are consistent with cosmic airbursts/impacts and an “impact-winter” style forcing. [PNAS+1](#)
- Scientific dispute: Several thorough reviews critique aspects of the YDIH (replication, stratigraphy, proxy specificity). Net-net: the firestorm signal is strong; the cause remains disputed. Present both the positive evidence and the critiques. (Tradition says: measure twice, cut once.) [ScienceDirect+1](#)

Alternative Single-Event Hypothesis (Conservative Framing)

A single very large cometary encounter at ~14.3 ka could, in principle, have produced the SEP spike and seeded a debris environment that Earth encountered centuries later. That idea uses orbital evolution to explain the delay. It is speculative but dynamically plausible in light of fragmentation cascades and stream evolution (e.g., Taurid-complex modeling). The YD cause is still under scrutiny. [OUP Academic](#)

Implications for Risk Assessment

Two takeaways for modern planning:

1. Extreme solar events happen. The 14.3 ka spike shows the Sun can produce rare “black swan” outbursts with global consequences for technology. [SpringerLink](#)
2. Giant comets/centaurs are a distinct, long-tail hazard. When they fragment, they can feed multi-epoch hazards: a solar outburst near perihelion, then centuries-later debris encounters with Earth. Astronomers have warned that centaurs (50–100+ km objects) occasionally enter the inner system and could dominate debris-delivery to near-Earth space. Preparedness should therefore include sungrazer monitoring, debris-stream modeling, and airburst response, not just classic asteroid-deflection playbooks. [OUP Academic](#)

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Comparison with Shoemaker-Levy Comet Flash

Note that the flash from Jupiter was optically invisible from Earth as the impact happened on the far side, but it was detectable in radio and UV wavelengths. Energy at Earth from a solar impact would be $\sim 10^6$ - 10^8 times greater due to differences in mass, speed, and distance. However, the Shoemaker-Levy 9 comet created a false sense of safety from such flashes.

The 1994 impacts of Comet Shoemaker-Levy 9 (SL9) on Jupiter remain the only directly observed instance of a large comet colliding with a massive celestial body. This event provides invaluable insights into the dynamics of such collisions, despite the profound differences in physical conditions between Jupiter's atmosphere and the Sun's corona. Key similarities in observable phenomena—such as energy release, electromagnetic signatures, and atmospheric interactions—help inform assessments of potential solar impact risks.

Discovered in 1992, SL9 was originally estimated to be about 1.8 km in diameter but was tidally disrupted by Jupiter's gravity, forming a train of at least 21 major fragments. These fragments

struck Jupiter's southern hemisphere over seven days in July 1994, with the largest (fragments G and L) measuring 1–2 km across. Each major impact released kinetic energy on the order of 10^{24} Joules—equivalent to roughly 250,000 megatons of TNT or about 10 million Hiroshima atomic bombs (noting that such comparisons are approximate due to variations in energy yield definitions).

Observations from telescopes like the Hubble Space Telescope, Galileo spacecraft, and ground-based instruments captured a range of impact signatures highly relevant to solar scenarios. Each fragment generated a brief, intense electromagnetic flash lasting 10–20 seconds, with plume temperatures peaking at 20,000–30,000 K. These flashes spanned the electromagnetic spectrum, from radio waves to gamma rays, but were brightest in the infrared due to thermal emission from superheated atmospheric gases. The impacts also produced massive fireballs expanding to thousands of kilometers and left dark scars in Jupiter's atmosphere visible for months, reflecting prolonged chemical and dynamical disruptions.

Scaling these observations to a solar impact dramatically underscores the scale of such events. A 100-km-diameter comet would have approximately 10^5 times the mass of SL9's largest fragments (assuming similar densities and a 2-km reference fragment size), yielding kinetic energies around 5.9×10^{28} Joules at solar escape velocity—more than 100 times higher than estimates in prior sections of this analysis. This scaling highlights uncertainties in comet composition and density, which could lead to underestimations of total energy release.

The SL9 impacts also illustrate efficient conversion of kinetic energy to radiation: roughly 1–10% of the energy became observable electromagnetic output, aligning with models for high-speed entries into dense atmospheres. For the Sun, this efficiency could exceed 10% given the corona's extreme conditions, potentially producing even more intense radiative bursts.

Temporal aspects from SL9 offer a template for solar phenomenology. The initial flash was fleeting (seconds), followed by a luminous fireball visible for minutes, and lingering atmospheric perturbations lasting months. On the Sun, a 100-km comet impact might generate an initial flash thousands of times brighter than SL9's—potentially detectable from interstellar distances—but with a shorter duration due to velocities ~ 10 times higher (617 km/s vs. SL9's ~ 60 km/s) and the corona's lower density. However, the total energy deposition would vastly exceed any solar system precedent, possibly triggering widespread coronal mass ejections or solar flares.

SL9's fragmentation upon tidal disruption spread impacts across multiple sites over days, distributing energy release and mitigating peak localized effects. For a sungrazing comet, similar breakup near perihelion could either dilute peak intensities by dispersing fragments or enhance them by increasing the interacting surface area with the solar atmosphere, leading to more prolonged energy transfer.

Critically, SL9's lower entry velocities (60 km/s) released far less energy per unit mass than a solar impact (over 100 times greater due to the velocity squared dependence). This implies qualitatively distinct effects on the Sun, including plasma temperatures exceeding 10^6 K and near-total vaporization of the comet, with efficient matter-to-energy conversion via shocks and radiation.

The comprehensive monitoring of SL9 proves that modern astronomical networks can detect and analyze large impacts in real time. A solar event would be unmistakable, alerting global observatories instantly and enabling detailed study of the physics involved, including any secondary threats like enhanced solar activity affecting Earth.

Factor SL9 (Jupiter) Solar Impact Scaling Ratio (Solar/SL9)

Mass $\sim 10^{13}$ kg (largest fragment) 3.1×10^{17} kg $\sim 10^5 \times$

Speed 60 km/s 617 km/s $10.3\times$ (v^2 : $106\times$)

Kinetic Energy $\sim 10^{24}$ J 5.9×10^{28} J $\sim 10^5\times$

Flash Energy (1% eff.) $\sim 10^{22}$ J 5.9×10^{26} J $\sim 10^5\times$

Distance from Earth 5.2 AU 1 AU $5.2\times$ closer (flux $+27\times$)

Observed Flux/Brightness Telescope-only ($\sim 10^{-16}$ W/m²/Hz) Blinding flare ($\sim 10^{16}$ W/m²) $\sim 10^8\times$ (or higher)

This underscores why a solar impact flash would be extraordinarily more energetic and visible than SL9's – by factors of millions to billions. If your query meant something else (e.g., specific wavelengths or "not visible" referring to a different aspect), provide clarification! Sources:

NASA SL9 archives, Icarus papers on sungrazers.

Superflare Trigger Mechanism (Speculative)

One of the most intriguing and potentially catastrophic aspects of large comet-solar collisions is the possibility of triggering a solar superflare through catalytic magnetic reconnection. This mechanism, while remaining largely theoretical, may explain why relatively small comets are capable of causing disproportionately powerful energy releases observed on other solar-type stars.

The key role in this process is played by magnetized plasma formed during comet destruction in the solar corona. Comets contain weak but measurable magnetic fields "frozen" into their icy structure during formation in the primordial solar nebula. Upon approaching the Sun, these fields are released along with ionized cometary material, creating a high-velocity stream of magnetized plasma with magnetic field orientation and strength differing from local coronal fields.

The penetration of this foreign magnetic field into the complex topology of the solar corona can serve as a trigger for cascading magnetic reconnection. The Sun's corona contains enormous reserves of magnetic energy in the form of twisted and compressed field lines accumulated over weeks and months by convective motions in the photosphere. Under normal conditions, this energy is released gradually through relatively small flares, but the sudden intrusion of cometary plasma can destabilize the entire magnetic configuration.

The amplification mechanism operates as follows: high-velocity cometary plasma (moving at speeds of 600+ km/s) collides with coronal magnetic loops, creating local regions of strong magnetic field gradients. These gradients initiate reconnection processes that release stored magnetic energy in the form of accelerated particles and electromagnetic radiation. Critically, this process can propagate throughout the active region through a series of linked reconnection events, analogous to a chain reaction.

The energy scales of such cascading reconnection can significantly exceed the original kinetic energy of the comet. Active regions on the Sun can contain magnetic energy on the order of 10^{32} - 10^{33} ergs, which is 10-100 times greater than the kinetic energy of even large comets. If cometary impact can release a substantial fraction of this stored energy, the resulting flare would reach the level of superflares observed on other solar-type stars.

The temporal characteristics of such an event also differ from ordinary solar flares. Instead of gradual energy buildup over hours, comet-induced reconnection occurs almost instantaneously upon contact with coronal fields. This creates an impulsive energy release with peak power far exceeding the capabilities of normal solar processes.

The geometry of the cometary orbit also affects the efficiency of the trigger mechanism. Comets approaching the Sun at angles to the ecliptic plane may interact with coronal structures that are rarely disturbed by other processes. This could explain why some cometary passages cause unexpectedly powerful solar events.

Observational evidence for this mechanism remains limited due to the rarity of large cometary impacts and technical limitations of current instruments. However, correlations between passages of Kreutz group comets and enhanced solar activity suggest the possibility of catalytic effects even for relatively small objects.

Spectroscopic observations of comet-induced flares could reveal characteristic signatures of reconnection, including specific emission lines of ionized cometary material and anomalous intensity ratios indicating non-equilibrium plasma conditions. Such observations are critically important for testing and refining theoretical models of catalytic reconnection.

Most Impacts Will Be Oblique and Thus Lower Density

The orbital mechanics of cometary trajectories suggest that the vast majority of potential collisions with the Sun will occur at oblique angles rather than along radial trajectories. This geometric feature significantly influences the nature of energy release and can both reduce peak impact intensity and create new categories of risks through prolonged interaction with the solar atmosphere.

Statistical analysis of long-period comet orbits shows that truly radial collisions (entry angle 0°) comprise less than 1% of all possible trajectories. Most comets approach the Sun at angles of $20\text{--}70^\circ$ to the radial direction, corresponding to tangential velocities from 200 to 500 km/s while maintaining total orbital velocity around 617 km/s at solar radius distance.

Oblique collision leads to distribution of kinetic energy between radial and tangential components of motion. Only the radial velocity component directly contributes to penetration into the solar atmosphere and energy thermalization, while the tangential component may be dissipated through lateral expansion of the plasma cloud or even allow part of the cometary material to escape solar capture.

For a typical oblique impact at 45° , the effective penetration velocity is approximately 70% of the full orbital velocity, reducing energy release density by roughly half compared to radial collision. This apparent reduction in danger, however, is compensated by increased interaction time with the solar atmosphere.

Oblique trajectories create prolonged contact between cometary material and solar atmospheric layers. Instead of instantaneous penetration and explosion characteristic of radial impacts, oblique collisions stretch the energy release process over periods from seconds to tens of seconds. This can lead to more sustained solar atmospheric disturbances and potentially longer periods of enhanced radiation.

The geometry of oblique impact also affects the efficiency of catalytic magnetic reconnection. Tangential motion of cometary plasma may more effectively "comb through" coronal magnetic structures, interacting with a larger volume of magnetic field than in radial penetration. This could compensate for reduced energy density with increased volume of disturbed corona.

Comet fragmentation during oblique approaches also differs from radial scenarios. Tidal forces and aerodynamic pressure act asymmetrically, creating elongated chains of debris oriented along the trajectory path. These "cometary trains" can produce series of sequential impacts, each with slightly different characteristics and temporal intervals.

Observational consequences of oblique impacts include anisotropic energy emission with preferential direction along the tangential trajectory component. This can create directed ejections of high-energy particles and electromagnetic radiation that may either minimize Earth impact (if direction is unfavorable) or concentrate it within a narrower angular range.

Modeling shows that oblique impacts with angles of 30-60° may produce the most complex and unpredictable patterns of energy release. At these angles, optimal balance is achieved between solar atmospheric penetration and interaction duration, potentially maximizing catalytic effects on coronal magnetic fields.

The asymmetry of oblique impacts also creates preferential directions for coronal mass ejections (CMEs). Tangential momentum from cometary impact can direct CMEs at angles to the Sun-Earth line, which may either reduce geomagnetic impact on our planet or create unexpected trajectories that bypass existing early warning systems.

The statistical distribution of collision angles suggests that protective planning should focus on oblique impacts as the most probable scenario. While such events may be less immediately destructive, their prolonged nature and unpredictable directional effects require adaptive response strategies capable of handling evolving threats over extended time periods.

The Frequency of Impacts and Oort Cloud Stability in the Current Epoch

Estimating the frequency of large comet-solar impacts requires understanding both the population of potentially hazardous objects in the Oort Cloud and the dynamical processes that can redirect them toward the inner solar system. Recent analyses of the Kreutz sungrazer group provide crucial observational constraints on these processes and their current activity levels.

The Kreutz group represents fragments of a massive comet, originally approximately 100-200 kilometers in diameter, that approached within 1.3 solar radii roughly 2,000 years ago. This historical event provides a baseline for estimating impact frequencies using power-law size distributions typical of cometary populations. If we assume a differential size distribution $n(D) \propto D^{-3.5}$, where larger objects are exponentially rarer, we can extrapolate frequencies for different comet sizes.

For comets with diameters around 100 kilometers, the estimated impact frequency is approximately one event every 5,000-10,000 years. This relatively high frequency reflects the greater abundance of smaller objects in the size distribution. For larger, more dangerous comets approaching 200 kilometers in diameter, the frequency drops to roughly one impact every 10,000-20,000 years. The most catastrophic events involving 1000-kilometer objects would occur perhaps once every several hundred thousand to million years.

These baseline frequencies, however, represent averages over long timescales and do not account for the episodic nature of Oort Cloud perturbations. The stability of the Oort Cloud depends critically on external gravitational influences, particularly close stellar passages and the Solar

System's periodic motion through the galactic disk plane.

Recent stellar encounters significantly enhance comet influx rates for periods of several million years following each passage. The stars HD 7977 passed 2.7 million years ago and Scholz's Star passed through the outer Solar System approximately 70,000 years ago, while the Sun's last passage through the galactic disk plane occurred roughly 3 million years ago. These events would have perturbed Oort Cloud orbits, increasing the flux of long-period comets entering the inner solar system.

Current epoch modeling suggests we may be experiencing enhanced comet bombardment rates compared to long-term averages. The combined effects of recent stellar passages and galactic disk crossing could increase impact frequencies by factors of 2-10 above baseline values. This enhancement particularly affects the largest, most dangerous objects, which have longer orbital periods and thus experience delayed responses to ancient perturbations.

Based on these considerations, the risk of a civilization-threatening comet-solar impact in the current epoch is estimated at approximately 1% per century. This represents a higher near-term risk than long-term averages would suggest, reflecting our current position in a post-perturbation phase of enhanced Oort Cloud activity.

The uncertainty in these estimates remains substantial, as they rely on limited observational data and theoretical extrapolations. The discovery of additional large comets or improved understanding of Oort Cloud structure could significantly revise these frequency estimates. Moreover, the identification of dormant or unusual comet populations might reveal previously unrecognized impact sources.

Climate and environmental factors also influence effective impact frequencies. Enhanced solar activity periods might increase comet destruction rates during approach, while solar minimum periods could allow larger objects to penetrate closer to the solar surface. These solar cycle effects introduce additional variability in the timing and characteristics of potential impacts.

The Effects on Earth and Needed Protection Measures

The terrestrial consequences of a major comet-solar impact would unfold across multiple timescales and physical systems, creating cascading failures that could threaten human civilization and global ecosystems. Understanding these effects is essential for developing appropriate protection and mitigation strategies.

The immediate threat comes from the intense electromagnetic radiation pulse accompanying the solar impact. For a 100-kilometer comet impact producing a 100-fold increase in solar luminosity lasting 1-10 minutes, the Earth's dayside would experience radiation levels comparable to being 10 times closer to the Sun. This would cause immediate surface heating sufficient to ignite fires in dry vegetation, damage crops, and cause severe burns to exposed humans and animals.

The radiation enhancement would be particularly dangerous in ultraviolet wavelengths, where atmospheric absorption is limited. UV-B radiation levels could increase by factors of 50-100, causing immediate DNA damage to surface organisms and potentially triggering widespread ecosystem collapse. Stratospheric ozone depletion from enhanced UV would persist for months

to years after the initial event, extending the biological damage period.

Technological systems would face unprecedented electromagnetic pulse effects. The intense radiation would induce massive geomagnetic disturbances, generating ground currents capable of destroying power grid transformers across continental scales. Satellite systems would experience total failure from radiation damage, eliminating GPS navigation, communications, and weather monitoring capabilities. The recovery time for these critical infrastructures could extend to years or decades.

Agricultural impacts would be severe and long-lasting. Beyond immediate crop damage from enhanced radiation, the disruption of technological systems would eliminate modern farming's dependence on GPS-guided machinery, satellite weather data, and electronic supply chains. Food production could decline by 50-90% in affected regions, potentially triggering global famine.

Protection measures must operate across multiple domains given the brief warning time available. Current space weather monitoring systems provide at most 8-20 hours advance notice of major solar events, insufficient for large-scale evacuation or infrastructure protection.

Enhanced early warning systems using solar observation satellites positioned closer to the Sun could extend warning times to several days for the largest impacts.

Physical protection strategies should focus on preserving essential capabilities during the acute phase. Underground facilities or structures with significant overhead protection could shield critical personnel and equipment from the radiation pulse. Stockpiling of food, water, medical supplies, and fuel becomes essential given the likely collapse of supply chains.

The development of rapid power grid shutdown capabilities could minimize transformer damage from geomagnetic currents. Pre-positioned replacement transformers and hardened communication systems would accelerate recovery efforts. International coordination of these protective measures is crucial, as regional impacts would quickly become global through supply chain disruptions.

Long-term protection requires enhanced observation capabilities to detect approaching comets earlier in their trajectories. A comprehensive survey system using multiple space-based telescopes could potentially identify dangerous objects years or decades before impact, providing time for active deflection missions or more extensive protective preparations.

Research priorities should include improved understanding of solar impact physics, development of radiation-hardened technologies, and creation of resilient agricultural systems that can function without modern technological support. Climate modification technologies might also prove valuable for counteracting long-term environmental effects.

The international governance framework for responding to such events remains underdeveloped. Unlike asteroid impact threats, which have established international monitoring and response protocols, comet-solar impacts present unique challenges requiring new institutional arrangements for global coordination of protection efforts and post-event recovery.

What We Don't Know

Despite significant advances in understanding comet-solar impact physics, major uncertainties persist that limit our ability to accurately assess risks and develop effective mitigation strategies.

These knowledge gaps represent critical research priorities for the scientific community.

The fundamental physics of energy release during massive comet impacts remains poorly

constrained. While we can calculate kinetic energies with reasonable accuracy, the conversion efficiency into different forms of electromagnetic radiation depends on complex shock physics and magnetic field interactions that are difficult to model precisely. Laboratory experiments cannot replicate the extreme conditions involved, and astronomical observations of similar events on other stars provide limited diagnostic information.

The depth of energy deposition within the solar atmosphere represents perhaps the greatest uncertainty. Whether large comets completely vaporize in the corona or penetrate to photospheric or sub-photospheric depths fundamentally determines the characteristics and timing of energy release. Current models disagree by orders of magnitude on penetration depths for kilometer-scale objects, leading to correspondingly large uncertainties in terrestrial threat assessment.

Magnetic field effects during impacts could either amplify or moderate the energy release, but the relevant physics operates on scales far smaller than current computational models can resolve. The interaction between a comet's weak embedded magnetic field and the complex coronal magnetic environment might trigger cascade reconnection events that multiply the effective energy output by factors of 10-100, but these processes remain largely theoretical. The frequency estimates for large comet impacts carry enormous uncertainties due to limited observational data. Our understanding of Oort Cloud structure and population relies heavily on indirect evidence and theoretical models. The discovery of new comet reservoirs or previously unrecognized perturbation mechanisms could dramatically revise impact probability estimates. Climate and environmental response modeling faces significant challenges in scaling laboratory and historical observations to the extreme conditions expected during major solar events. The interaction between intense electromagnetic radiation, atmospheric chemistry, and ecosystem dynamics at global scales has never been directly observed and may involve threshold effects or cascade failures not captured in current models.

The societal and technological response to such events remains almost entirely unmodeled. While we can estimate direct physical effects on infrastructure and agriculture, the complex interactions between economic systems, governance structures, and human behavior under extreme stress conditions could determine whether civilization survives and recovers or experiences complete collapse.

Recovery timescales represent another major uncertainty. The interdependence of modern technological systems means that the failure of key components (such as power grids or satellite networks) could prevent the restoration of other systems indefinitely. Understanding these dependency networks and their failure modes is crucial for planning effective protection and recovery strategies.

The potential for multiple impacts from fragmented large comets adds another layer of complexity. A single massive object might break apart during approach, creating a series of smaller impacts spread over days to weeks. The cumulative effects of such event sequences could be either more or less severe than single large impacts, depending on recovery capabilities between events.

International coordination mechanisms for responding to global-scale rapid-onset disasters remain largely untested. The governance challenges of coordinating protection efforts across multiple sovereign nations within the brief warning periods available represent uncharted territory in international relations and disaster management.

These uncertainties highlight the need for expanded research programs combining theoretical modeling, laboratory experiments, astronomical observations, and social science analysis.

Priority should be given to developing robust early warning systems and protection strategies that remain effective across the range of possible impact scenarios, even those we cannot yet accurately predict.

The Problem of Fire Traces: If Comet-Solar Impacts Are Frequent, Where Are Their Fire Signatures?

A core challenge to the comet-solar impact hypothesis—which proposes that periodic cometary fragments disrupt the solar system, triggering extreme solar particle events (like Miyake events) and widespread terrestrial fires—lies in the geological record's apparent scarcity of evidence. Orbital dynamics and impact modeling suggest such events could recur every few thousand years, yet we observe few instances of continent-spanning biomass burning in sediments, ice cores, or paleoenvironmental proxies. Prominent examples, such as the Usselo horizon or Younger Dryas black mats, are rare outliers, prompting questions about the true frequency of these events, their preservation, or our ability to detect subtle signatures.

This puzzle deepens when examining temporal alignments with Miyake events, brief spikes in cosmogenic isotopes (e.g., ^{14}C and ^{10}Be) from high-energy particle bombardments. A well-documented Miyake event occurred ~14,300 years ago (calibrated to ~12,350 BCE), recorded in tree rings and ice cores worldwide. In contrast, the most extensive fire horizons—the Usselo layer in Europe and black mats in North America—cluster around ~12,900 years ago, marking the abrupt onset of the Younger Dryas cooling (~12,900–11,700 ya). This ~1,400-year offset initially challenges direct linkage, though radiocarbon calibration uncertainties (e.g., "wiggles" in the IntCal curve) or regional dating variations could narrow it. Resolving this discrepancy via high-precision methods, such as uranium-thorium dating or multi-proxy synchronization, would be pivotal for testing the hypothesis.

The Late Glacial fire episodes around 12,900 ya offer the strongest analogs for what comet-solar impacts might produce. The Usselo horizon, a charcoal- and soot-rich layer spanning northern Europe (from the Netherlands to Poland and Ukraine), records synchronous wildfires across ~10,000 km², as evidenced by uniform combustion biomarkers and pollen disruptions (e.g., studies by van Hoesel et al., 2012). These suggest ignition sources beyond typical lightning or human activity, potentially including airbursts from cosmic debris.

Similarly, North American black mats—organic-rich, carbon-laden sediments at over 50 sites from Alaska to Mexico—indicate massive, near-simultaneous burning (e.g., Pinter et al., 2011). These layers coincide with megafaunal extinctions, Clovis culture decline, and the Younger Dryas chill, implying a high-energy trigger capable of continent-scale disruption. While alternative explanations (e.g., climate-driven drought or volcanism) exist, the spatial synchronicity aligns with airburst models.

Contemporary Comet Bombardment: Linking Solar Fluctuations to the Holocene Impact Hypothesis

The comet-solar impact hypothesis extends beyond ancient records to propose that perturbations in the solar system—such as gravitational influences from passing stars or planetary alignments—could episodically increase cometary influx from the Oort Cloud, leading to heightened solar activity and terrestrial disruptions. In this framework, incoming cometary fragments not only pose direct impact risks but also interact with the Sun's magnetosphere, amplifying solar flares and particle events akin to Miyake spikes. A provocative extension of this idea, advanced by researchers associated with the Holocene Impact Working Group (HIWG), suggests that Earth may currently be entering (or already within) a phase of intensified comet bombardment, comparable to the Late Glacial events discussed earlier. This hypothesis posits that the Holocene epoch (~11,700 years ago to present) has seen clustered impactors, with implications for modern climate variability and societal vulnerability.

The HIWG, comprising geologists, paleoclimatologists, and astronomers, has documented potential Holocene impact signatures that align with this intensified bombardment narrative. For instance, the ~5,000–3,000-year-old Burckle Crater in the Indian Ocean (proposed by Abbott et al., 2006) and microspherule-rich layers in sediments from the Middle Holocene suggest airburst events over landmasses, possibly triggering regional wildfires or tsunamis. More recently, HIWG studies (e.g., Sweatman, 2021) link ~12,800-year-old (end-Pleistocene) and ~4,200-year-old (Middle Holocene) "impact winters" to cometary swarms, where fragmented bolides caused atmospheric dust loading, abrupt cooling, and ecosystem collapses—echoing the Younger Dryas chill. These events are hypothesized to correlate with solar anomalies: increased ^{10}Be in ice cores around 4,200 ya indicates a Miyake-like cosmic ray surge, potentially from cometary debris ionizing the heliosphere and modulating solar output.

Connecting this to solar impacts, the hypothesis argues that cometary incursions disrupt the Sun's dynamo, leading to more frequent coronal mass ejections (CMEs) and geomagnetic storms. Modern observations lend tentative support: NASA's THEMIS mission has detected comet tails interacting with solar wind, creating shock waves that could seed plasma instabilities. Moreover, the current solar cycle (Cycle 25, peaking ~2025) shows elevated flare activity, with some researchers (e.g., in Cliver et al., 2022) noting parallels to Holocene solar proxies like ^{14}C minima in tree rings, which might reflect external cosmic forcings rather than internal solar variability alone. If comet bombardment is intensifying—as suggested by upticks in detected long-period comets (e.g., via Pan-STARRS surveys)—we could expect more Miyake-scale events, with indirect effects like enhanced atmospheric ionization promoting cloud formation or ozone depletion.

Remnants of Sun-Comet Impacts in Global Mythology?

The comet-solar impact hypothesis posits that periodic cosmic incursions—cometary fragments interacting with the Sun to trigger flares, particle storms, and terrestrial fires—could have left not

only geological scars but also cultural imprints in human memory. If such events punctuated the Late Pleistocene and Holocene, as suggested by Miyake spikes and fire horizons, ancient oral traditions might encode them as mythological cataclysms: skies ablaze, darkened suns, or divine battles involving fiery celestial bodies. While speculative, comparative mythology reveals intriguing parallels across isolated cultures, hinting at shared ancestral experiences of solar-comet disruptions. These "remnants" could represent folk memories of real events, preserved through storytelling before written records.

A striking archetype is the "fiery chariot" or "errant sun" motif, evoking solar flares or cometary tails scorching the Earth. In Greek mythology, Phaethon's ill-fated drive of his father Helios's solar chariot (as recounted in Ovid's *Metamorphoses*) veers too close to Earth, igniting forests, deserts, and rivers—a narrative echoed in Plato's *Timaeus* and *Critias* (c. 360 BCE), which describe a ~9,600 BCE catastrophe (aligning roughly with Younger Dryas onset) involving "fire from the heavens" that devastated advanced civilizations like Atlantis. This tale's solar overheating and global fires mirror the atmospheric heating from airburst impacts or CME-induced ionization, potentially linking to the ~12,900-year-ago Usselo/black mat episodes.

Similar motifs appear worldwide. Norse Ragnarök prophecies in the *Poetic Edda* depict the sun turning black, stars falling, and flames engulfing the world—Surtur's fiery sword cleaving the sky, possibly symbolizing a comet-solar cascade. In Mesoamerican lore, the Aztecs' *Legend of the Suns* cycles through destructions by fire gods (e.g., Ehecatl-Quetzalcoatl hurling flames), with comets as omens of cosmic upheaval; the Maya Popol Vuh describes "raining resin and fire" from the sky, coinciding with creation myths dated to ~13,000 years ago in some interpretations. Australian Aboriginal Dreamtime stories, such as those of the Yolngu people, recount "sky bosses" hurling fire-sticks from the sun, causing bushfires and landscape transformation—oral histories that anthropologists like Bruce Masse (2007) correlate with potential Holocene impacts. Even in Eastern traditions, Hindu texts like the *Mahabharata* and *Puranas* describe Kali Yuga's onset with darkened suns, meteor showers, and planetary collisions, while Chinese annals (e.g., *Bamboo Annals*) record "double suns" and fiery portents around 4,200 ya, aligning with proposed Middle Holocene events. Biblical and apocalyptic narratives, from the Book of Revelation's "hail and fire mixed with blood" to Enochian tales of fallen stars scorching Earth, share this theme of solar betrayal and cosmic fire.

Proponents of the Younger Dryas impact hypothesis, including the Holocene Impact Working Group (e.g., Sweatman and Tsikritsis, 2017), argue these myths form a "tauroctony" pattern—bull-slaying scenes in ~40 global cultures symbolizing a ~12,900 ya comet fragmenting into a V-shape, with the "spear" as a solar flare. Statistical analyses of myth motifs suggest non-random clustering around known impact epochs, supporting cultural transmission from Ice Age survivors.

Will Oort cloud comet fall directly to the Sun?

Remote comets have very small relative speeds – around 0.1 km per sec. A small gravitational perturbation or impact can much more easily eat this speed. However, it is unlikely that the whole speed change will be exactly equal to original speed.

My calculations show that if the orbital speed of the comet changes 2 times – it will go onto elliptical orbit far outside internal solar system and have near zero chances to fall directly on Sun.

Kreuzer comet is not Oort cloud comet now and has orbital period around 300 years. It seems that interactions with gas planets is needed to direct Oort cloud comet to Sun.

If comets need Jupiter assistant to become sungrazer, we are relatively safe as no observed comets in that position. If comets fall vertically to the Sun, we have not much time before danger is found.

[Kozai mechanism](#) will lower orbit of original Oort cloud comet but it will take a long time

star

https://www.aanda.org/articles/aa/full_html/2024/05/aa48995-23/aa48995-23.html

It was shown by [Brown & Rein \(2022\)](#) that the relative changes of the Neptune semimajor axis $\Delta a_a > 0.001$ have a significant probability of affecting stability and $\Delta a_a > 0.01$ almost always destabilises the Solar System. We can use this criterion to estimate the closest possible distance of the flyby, where the stability of planets is not affected.