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**2032 AND 2036 RISK ENHANCEMENT FROM NEOs IN THE TAURID STREAM;  
IS THERE A SIGNIFICANT COHERENT COMPONENT TO IMPACT RISK?**

**Mark Boslough<sup>(1,2)</sup>, Peter G. Brown<sup>(3)</sup>, David Clark<sup>(3)</sup>, Paul Wiegert<sup>(3)</sup>, and  
Quanzhi Ye<sup>(4)</sup>**

<sup>(1)</sup>Los Alamos National Laboratory, Los Alamos, NM, 87545, USA, [mbeb@lanl.gov](mailto:mbeb@lanl.gov),

<sup>(2)</sup>University of New Mexico, Albuquerque, NM, 87131, USA, [mbeb@unm.gov](mailto:mbeb@unm.gov), <sup>(3)</sup>  
University of Western Ontario, London, Ontario, N6A 5B7, Canada <sup>(4)</sup>Department of  
Astronomy, University of Maryland, College Park, MD 20742, USA

**Abstract**

Impact risk is normally quantified by summing the product of the probability of an event and some measure of its consequences over the set of all possible events. The probability factor is considered to be more objective and is based on the size frequency distribution of NEOs and an implicit assumption of randomness, which can be described as “stochastic risk”. Impact frequency does change with time, however, and there have been episodes in the deep geological past when the flux has been much higher. The hypothesis of “coherent catastrophism” suggests large variations on shorter timescales. It postulates the existence of a “Taurid resonant swarm” (TRS) of debris associated with Comet Encke that is stabilized by Jupiter and in a 7:2 resonance with it. The hypothetical cluster orbits in the broad Beta Taurid stream, which crosses Earth’s orbit twice a year at its nodes. Whereas the most extreme and fanciful versions of coherent catastrophism in recent geologic history have been comprehensively refuted, the possibility of a significant component of coherent risk remains a possibility. This paper incorporates recently published data from observational campaigns associated with the Taurid stream. There is no evidence for objects in the Taurid stream that are above the global catastrophe threshold, but the possibility of a few large objects and a significant population of objects the size of the Chelyabinsk or Tunguska bodies, has not been eliminated. Circumstantial evidence and comparison of airburst models to ground truth suggest that the Tunguska object was a Taurid. The Tunguska event is a probability outlier when compared to the size frequency distributions under stochastic assumptions, but if there is a significant coherent component it may represent events that take place far more frequently, and that risk assessments have underestimated the contribution from airbursts.

**Keywords:** *Beta Taurids, targeted surveys, Tunguska, coherent risk, stochastic risk*

**Introduction**

Theoretical calculations by Asher and Clube [1] suggest that the last close approaches, within 1° absolute mean anomaly difference  $|\Delta M|$  were in November 1971 and June 1975 for its perihelion approach and departure, respectively. Circumstantial evidence (large daytime fireballs and seismic activity on the moon at the time of the 1975 crossing) are consistent with an increase in the flux of larger fragments. Rates

and data for fireballs that correlated with the predicted 2015 return were recorded by Egal et al. [2]. Large uncertainties remain in the number of objects larger than meter-sized in the TRS, so its significance to risk remains poorly constrained and contentious. There is some evidence for a few objects large enough to be hazardous, associated with the 2015 swarm, but the population has not yet been shown to be statistically significant.

In 2019 and 2022, the predicted node crossings were close enough to attempt targeted surveys [3,4], with  $|\Delta M|$  of  $5^\circ$  and  $17^\circ$ , respectively, based on extrapolation of predicted swarm encounters [1]. Upcoming potential targeted survey opportunities will be 2025, 2026, and 2029 ( $|\Delta M|$  of  $25^\circ$ ,  $18^\circ$  and  $23^\circ$ , respectively). Targeted surveys provide the opportunity to put further constraints on the population of the hypothetical swarm as well as to determine potential future close passes or impacts if the swarm exists. The 7:2 resonance with Jupiter happens to come close to a 18:61 resonance with Earth, so the next set of  $1^\circ$  node crossings will be in 2032 and 2036, which would be years of increased impact probability. We also suggest that this possibility could form the basis for a semi-hypothetical tabletop exercise, based on the trajectory of the Tunguska object, which was in an orbit consistent with the Beta Taurid stream [5]

There is skepticism within the planetary defense community of coherent catastrophism due to misinformation, misunderstandings, and misinterpretations associated with the Younger Dryas impact hypothesis (YDIH) and its pseudoscientific corollary claims [6-8]. Nevertheless, the possibility of enhanced risk from an undiscovered population of small NEOs in the hypothetical TRS should not be dismissed unless comprehensive targeted surveys demonstrate that there is no significant population.

### **Stochastic Risk**

Shoemaker's 1983 review, "Asteroid and Comet Bombardment of the Earth" [9] was the first comprehensive assessment of the size frequency distribution of Earth crossing asteroids and comet nuclei, a subclass of what are now called Near Earth Objects (NEOs). He reviewed and compared the results of systematic telescopic surveys with discoveries of ancient terrestrial impact structures over the previous two decades. At the time of writing, only 49 Earth crossing asteroids had been discovered, and the average rate of discovery was about 3 per year. Shoemaker concluded, based on statistical analysis and using discovery rates to estimate the total population, that the mean probability of collision by asteroids brighter than absolute magnitude 18 was about 3.2 per million years. He highlighted the rough consistency between the present cratering rate by comparing this astronomical survey-based estimate to the rate derived from the geological record. He concluded that the population of Earth crossing asteroids has been in approximate equilibrium over the last 500 million years; their depletion through collisions and ejection has been balanced by the injection of new asteroids by gravitational perturbations.

The size-frequency distribution of lunar craters allowed Shoemaker to estimate the energy-frequency distribution of Earth-crossing objects smaller than the diameter threshold for telescopic observations at the time of about 500 m, and this enabled him to calculate a cumulative impact frequency per year as a function of impact energy (Fig. 1). The stochastic assumption was implicit, but there was almost no telescopic data for objects smaller than 500 m, and the dating of small lunar craters lacked

sufficient temporal resolution, robustness, or statistical significance to support the assumption of an unchanging impact rate over short time scales for small bodies. Shoemaker discussed the various size estimates (in terms of kinetic energy) ranging from 12 to 670 megatons, and argued for the lower estimate in part based on the much higher stochastic probability that an object of that size would have struck the earth only 75 years earlier:

*From Figure 1, it may be seen that the "best estimate" of the frequency of a 12-megaton encounter with the Earth is about once every 300  $\times/\div$  2 years; a 30-megaton encounter occurs about every 700  $\times/\div$  2 years. There is a  $\sim$  12 to  $\sim$  40% chance that a 12-megaton encounter will occur in an interval of 75 years (the approximate time elapsed since 1908) and a  $\sim$  5 to  $\sim$  20% chance that a 30-megaton event will occur during this interval. On the basis of the predicted frequency, estimates of the energy of the Tunguska event in the range of 10-15 megatons appear somewhat more likely than ReVelle's estimate of 30 megatons. There is no more than a 1.5% chance of an encounter of a 670-megaton bolide in an interval of 75 years.*

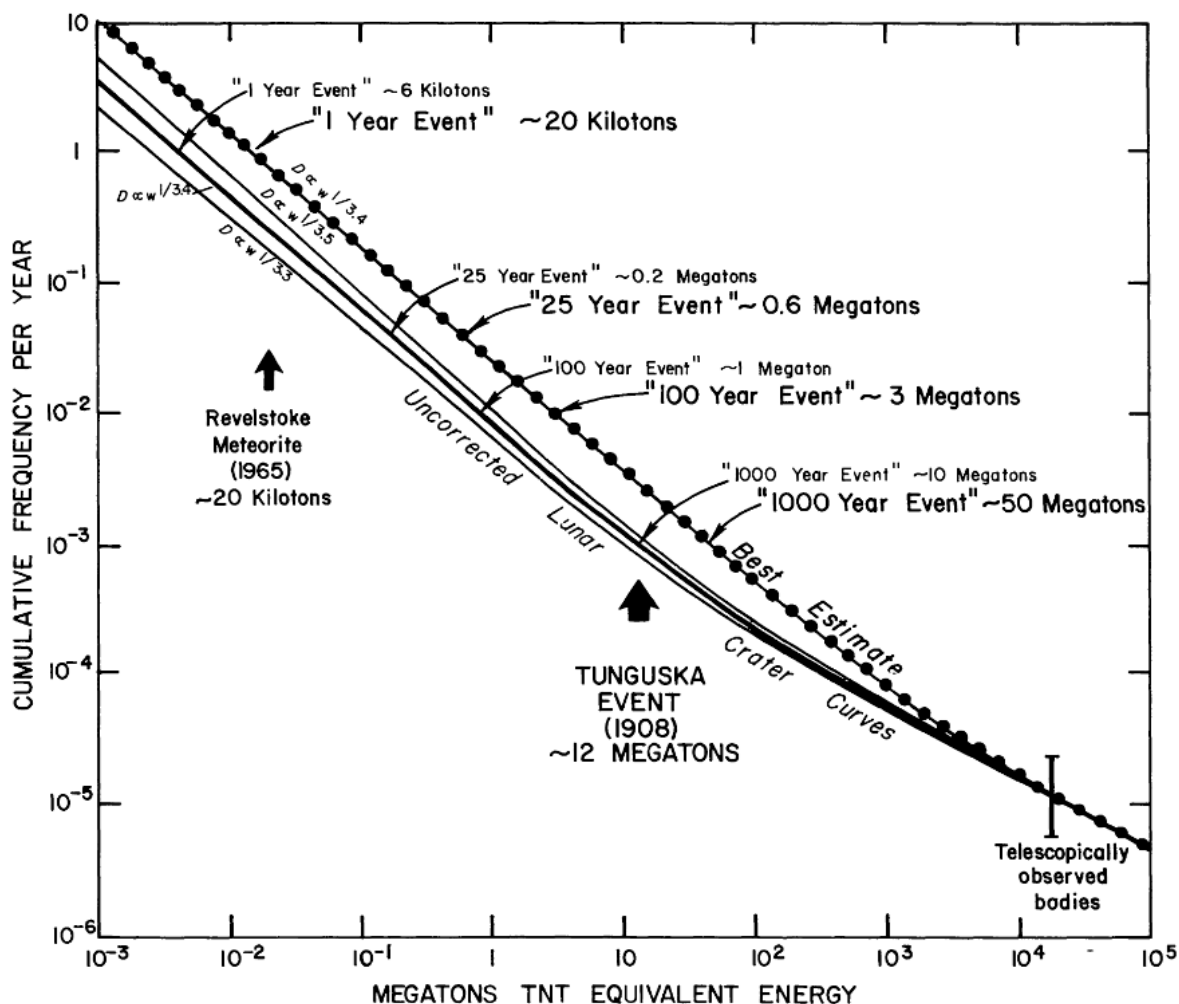
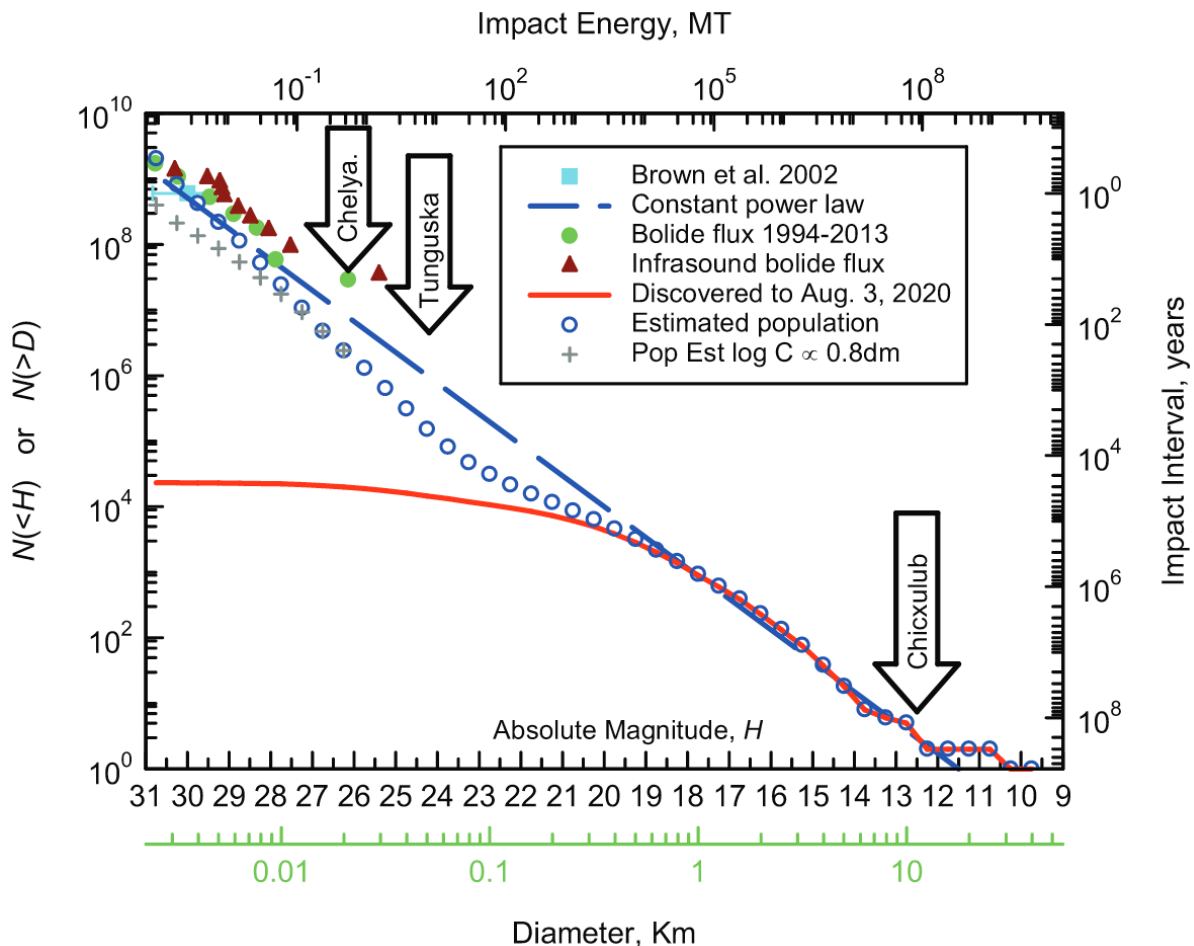


Fig. 1 Cumulative frequency distribution of impact energy for objects colliding with Earth, estimated by Shoemaker [9].

Shoemaker did not explicitly address impact risk, but did conclude with a section, “Effects of Bombardment on Terrestrial Life” which surveyed efforts to assess the effects of globally catastrophic impacts on the biosphere, including the recent discovery by Alvarez et al. [10] of the iridium anomaly at the end of the Cretaceous and the impact/extinction hypothesis. These advances in the 1980s led to the first impact risk assessment by Chapman and Morrison [11] in 1993, who adopted Shoemaker’s built-in stochastic assumption despite its lack of a robust foundation for small asteroids.

A version of Shoemaker’s 1983 cumulative frequency distribution graph is regularly updated to accommodate the accelerating rate of discoveries and the higher completion rates for smaller NEOs. This graph is a critical component of all probabilistic risk assessments for planetary defense. Notably, the 2021 update by Harris and Chodas [12] continues to show a large, order-of-magnitude deficit in the population of objects smaller than a few hundred meters relative to the best-fitting constant power law, as well as relative to Shoemaker’s estimate based on lunar crater counts.



The deficit in survey-based population estimates in the objects that are tens to hundreds of meters in diameter exacerbate the improbability problem Shoemaker identified with the higher-yield estimates for Tunguska. His preference for the estimates in the 10-15 megaton range was largely based on the fact that an object of this size was far more likely to have struck the Earth than a 30 megaton object, which

corresponded to an event that should happen only once every 700 years, give or take a factor of two. But according to the size frequency distribution graph of Harris and Chodas an impact of 12 Mt should only happen once every 7000 years. Even the lowest published estimate range of 3-5 Mt [13] for Tunguska should take place no more frequently than once every ~4000 years, and Chelyabinsk corresponds to a ~250 year event.

The size frequency distributions based on astronomical surveys appear to be inconsistent for objects that are tens to hundreds of meters in diameter, with the lunar cratering record and with the Tunguska and Chelyabinsk events both of which would have been extremely unlikely. One potential explanation for this inconsistency is the existence of a coherent population of NEOs that includes a significant number of objects that have not been observable, due to their orbital positions, since NEO surveys started in the 1990s.

### **Coherent Risk**

Shoemaker [9] was open to the possibility that the Tunguska object was a cometary object,

*Whipple (1930) suggested that the Tunguska object may have been a comet, and this concept appears to have gained general acceptance among informed Soviet investigators. Kresak (1978) has shown that the approximate trajectory of the meteor was consistent with the hypothesis that the Tunguska bolide was a fragment of Comet Encke. The strongest evidence that the Tunguska object was a comet comes from the distribution of very fine particles in the high atmosphere on the night following the encounter; an enormous, bright noctilucent cloud extended westward from Siberia to Ireland (1'-/ 6000 km) and as far south as 45°N latitude.*

A decade later, the comet he co-discovered (Shoemaker-Levy 9) collided with Jupiter and provided a better explanation for the noctilucent cloud of 1908: high-altitude condensate from a collapsed ballistic plume that was also observed on Jupiter [14,15]. Advances in computational modeling of airbursts has created the opportunity to test the Kresak's [16] association of Tunguska with Comet Encke by simulating of the air blast at the surface. We modeled the effects of an object with entry parameters (azimuth, entry angle, and velocity) consistent with the date, time of day, and location for the entry of a Beta Taurid object associated with Encke. The shape and orientation of the resulting blast wave footprint is a good match to published maps of tree fall (Figs. 3, 4).

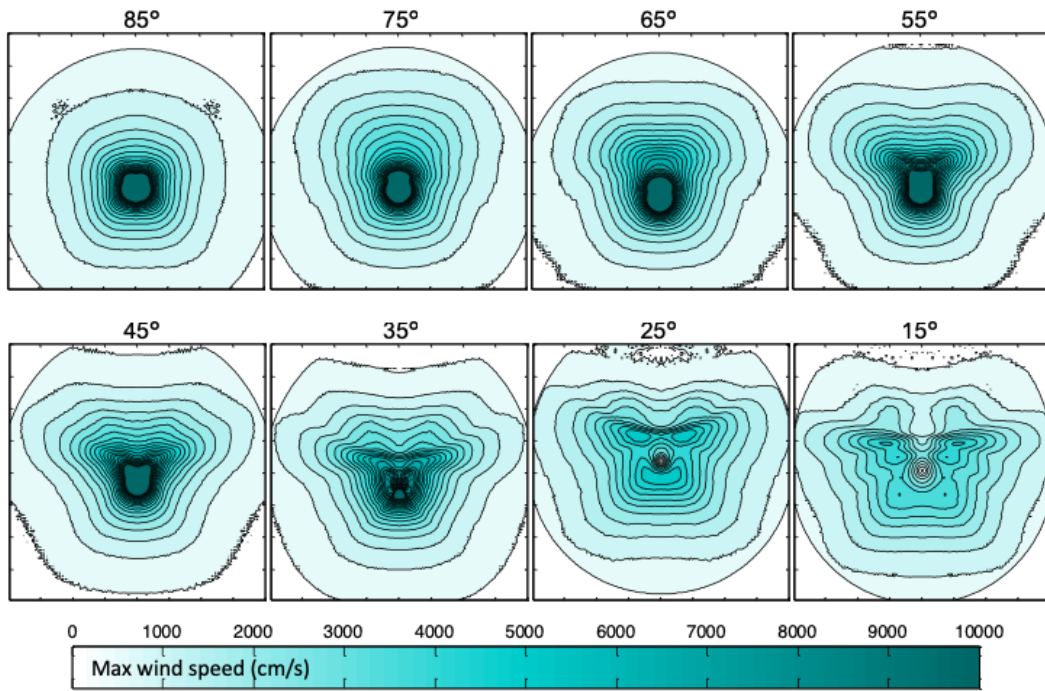


Fig 3. Series of 8 Mt airburst simulations showing that the entry angle range that best matches the observations of tree fall ranges from 25 to 45 degrees elevation.

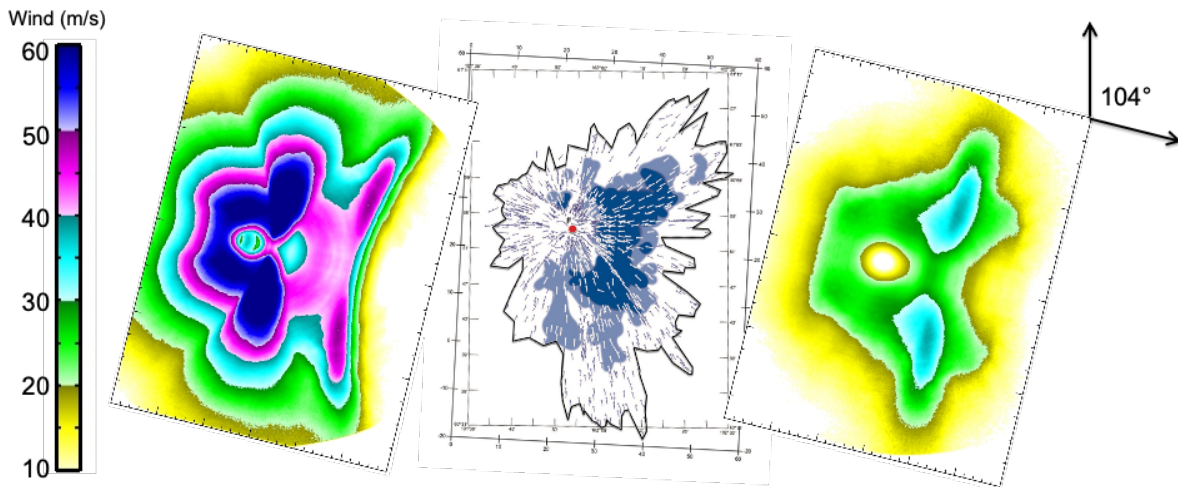


Fig. 4. Simulations provide best match to observed treefall data [17] for 5 Mt body entering at 35° elevation. Orientation of treefall symmetry suggests 104° entry azimuth. According to Brown et al. [18] a Beta Taurid radiant at Tunguska event time and location would imply a 32° elevation and 104° azimuth entry.

Shoemaker was open to episodes of coherent risk, having posthumously coauthored a 1998 paper suggesting evidence for a comet shower in the late Eocene [19]. Solid evidence for a shower of meteorites from a fragmented asteroid in the early Ordovician was published in 2001 [20]. There is significant evidence for the existence of a Taurid resonant swarm, which effectively provides an existence proof that risk cannot be assumed to be purely stochastic, and there is no theoretical or observational evidence

that coherent risk should be treated as negligible for NEOs that are tens to hundreds of meters in diameter.

The best argument for a coherent risk component, during recent geological time up to the present, comes from the theoretical calculations of Asher & Clube [1], which has been supported by observational evidence. The 1975 daytime Taurid resonant swarm has been associated with an order of magnitude increase in the impact rate on the Moon as measured by Apollo – era seismometers [21]. Moreover, the overall behavior of the Taurid resonant swarm and its apparent linkage with large meteoroids has been recently demonstrated through a large number of high precision fireball measurements of the 2015 nighttime (Taurid) resonant swarm return [22].

These measurements confirmed with high precision the apparent resonant swarm 7:2 MMR with Jupiter, showing that large meteoroids can be “shepherded and concentrated” by the resonance. In addition, several NEAs (2015 TX24 and 2005 UR with diameters of several hundred meters) were found to have orbits placing them inside the resonant branch, establishing that the enhancement in meteoroid spatial density due to the resonance extends from sub-mm sized meteoroids to large NEAs. This makes the connection with the Beta Taurids more plausible and suggests that both in-atmosphere and exo-atmosphere observational campaigns of the swarm could be productive. In Table 1 (adapted from [1]), Delta M is the encounter offset in units of Mean Anomaly (degrees) relative to the resonant swarm center.

Table 1. Adapted from Asher & Clube [1] where M is Mean Anomaly in degrees

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<b>Year (Jun)</b>	<b>Delta M</b>
1904	19
1907	-22
1914	2
1917	-40
1921	25
1924	-16
1931	7
1934	-34
1938	31
1941	-10
1948	13
1951	-28
1955	37
1958	-5
1965	19
1968	-22
1975	1
1982	25
1985	-17
1992	7
1995	-34
1999	30
<b>Year (Jun)</b>	<b>Delta M</b>
2002	-11
2009	13
2012	-29
2016	36
2019	-5
2026	18
2029	-23
2036	1

<b>Year (Nov)</b>	<b>Delta M</b>
1900	18
1903	-24
1910	0
1917	23
1920	-18
1927	6
1930	-36
1934	29
1937	-12
1944	11
1947	-30
1951	35
1954	-6
1961	17
1964	-24
1971	-1
1978	23
1981	-18
1988	5
1991	-36
1995	29
1998	-13
<b>Year (Nov)</b>	<b>Delta M</b>
2005	11
2008	-30
2012	35
2015	-7
2022	17
2025	-25
2032	-1
2039	23

The Tunguska connection to the Beta Taurids has been posited for some time [16] and within uncertainty, the trajectory for Tunguska fits with a Beta Taurid link. The timeliness of this connection is the expected return of the resonant Taurid swarm in 2032 and 2036 [1] which will be the closest Earth passes to the inbound leg (nighttime) and outbound leg (daytime) portion of the resonant stream since 1971 and 1975, respectively.

Large fireballs--some associated with meter-class impactors--were observed during the Nov, 2015 Taurid swarm return [22]. Additionally, several small asteroids--such as 2015 TX24--have orbits that are nearly identical to the 2015 Taurid fireball swarm [23,24]. When the Earth intersects with this stream, the probability of impact is elevated. If the Tunguska object was a member of a Beta Taurid stream (Kresák, 1978) then the last week in June 2019 will be the next occasion with a high probability for Tunguska-like collisions or near-misses [25]. Because the Beta Taurids approach from the sunward side, we propose a survey designed to observe such objects after they have passed into the night sky which would have little lunar interference because the moon is new on July 3, 2019. Moreover, the possibility of enhanced daylight fireballs and significant airbursts should be anticipated during that time.

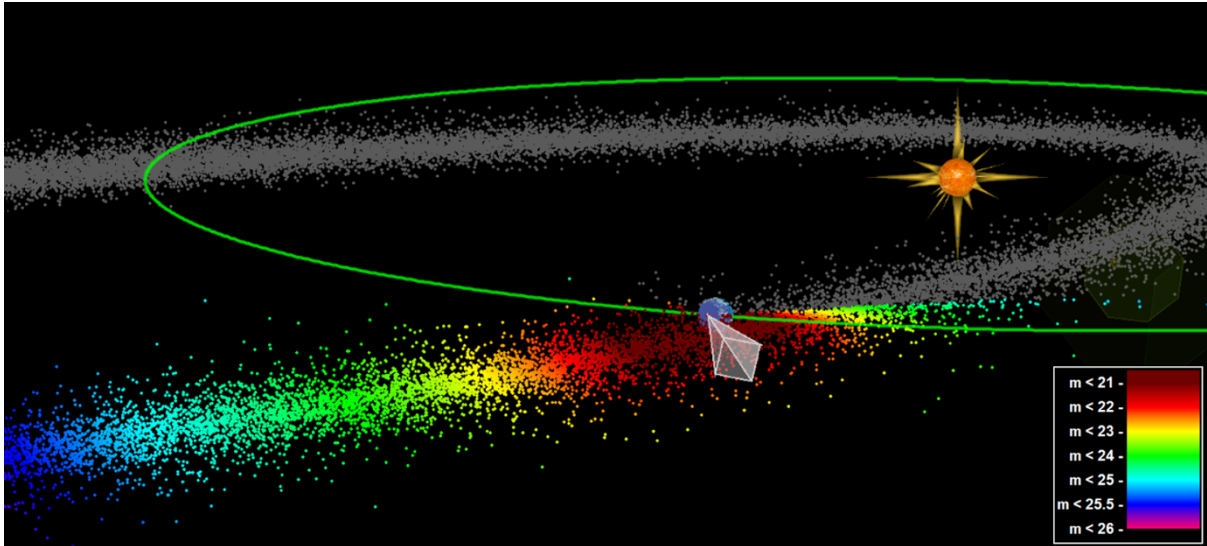


Fig. 4. Taurid stream geometry during the 2022 survey of Wiegert et al [28]. Polyhedron represents the volume of sampled space in a single CFHT image and colors represent the apparent magnitude of Taurids, normalized to a diameter of 100 m, as seen from Earth.

Dedicated surveys were attempted using the Canada-France-Hawaii Telescope (CFHT) on Mauna Kea in the summer of 2019, when the Taurid resonant swarm was predicted to pass Earth on its outbound leg by only 5 degrees Mean Anomaly magnitude (Table 1) but yielded no results due to an unscheduled interruption of the dedicated survey time [3,28]. Further observational searches were conducted with CFHT and Zwicky Transient Facility (ZTF) during the 2022 inbound apparition with mean anomaly magnitude of 17 degrees. The 2022 ZTF survey yielded no positive detections but provided bounds on the population, which yields <9-14 objects brighter than  $H=24$  [4]. Images obtained with the MegaCam imager over 3 nights (29 to 31 October, 2022), by Wiegert et al [27] during stream geometry depicted in Fig. 5 yielded an upper bound of fewer than 3,000 to 30,000 objects brighter than  $H=25.6 \pm 0.3$ ,

corresponding to a diameter of between 34 and 78 meters assuming an albedo consistent with comet Encke.

## Conclusions

Hydrocode models of the 1908 Tunguska airburst have provided reasonable explanations for most of the phenomena associated with that event, from the shape of the treefall pattern to the bright nights over western Europe [13,14]. Similar models are used to estimate the damage component of probabilistic risk assessment and cost/benefit analysis for planetary defense. Nevertheless, there is still an enormous range in model-based estimates of the size of the Tunguska impactor and explosive yield, from as low as 3 to as high as 30 megatons. This range of possible sizes, combined with NEO population estimates, leaves us with one unsatisfying conclusion: the Tunguska event was an extreme outlier. The probability of an impact of that magnitude having happened only 117 years ago is extremely low. The frequency of the smallest and largest possible Tunguska-like events (3 and 30 megatons), according to current survey-based size frequency distributions, would be on the order of once every 4,000 to less than one every 10,000 years, respectively.

One way out of this dilemma is to question a built-in assumption in our probability estimates that small NEOs are effectively distributed randomly. Whereas the most sensational claims of “coherent catastrophism” lack merit, it is reasonable to speculate that the Taurid complex has significant concentrations of Tunguska-sized fragments that are too small to be observed unless in the vicinity of the Earth. The Taurid resonant swarm is predicted to pass Earth within 1 degree mean anomaly on the inbound leg in November, 2032, and again on the outbound leg in June, 2036. If there is a significant, or even dominant contribution to the risk from the Taurid resonant swarm, then targeted surveys designed to detect potential impactors prior to these encounters should be prioritized. Surveys dedicated to the detection of imminent impactors during the passage of the swarm should also be implemented.

## References

- [1] Asher DJ, Clube SV. An extraterrestrial influence during the current glacial-interglacial. *Quarterly Journal of the Royal Astronomical Society*, Vol. 34: 4/DEC, P. 481-511, 1993. 1993 Dec;34:481-511.
- [2] Egal A, et al. An observational synthesis of the Taurid meteor complex. *Monthly Notices of the Royal Astronomical Society*. 2022 May;512(2):2318-36.
- [3] Clark, David L., Paul Wiegert, and Peter G. Brown. "The 2019 Taurid resonant swarm: prospects for ground detection of small NEOs." *Monthly Notices of the Royal Astronomical Society: Letters* 487.1 (2019): L35-L39.
- [4] Li J et al. Search of the Potentially Hazardous Asteroids in the Taurid Resonant Swarm. *Planetary Science Journal*, 6, 94.
- [5] Boslough M, et al. Analysis of the Tunguska Event as a Semi-Hypothetical Impact Scenario. 2023, American Geophysical Union Fall Meeting.
- [6] Holliday VT, et al. Comprehensive refutation of the Younger Dryas Impact Hypothesis (YDIH). *Earth-Science Reviews*. 2023 Dec 1;247:104502.

- [7] K.C. Nolan, et al., Refuting the sensational claim of a Hopewell-ending cosmic airburst. *Scientific Reports*, 13(1), 12910, 2023.
- [8] M. Boslough, A. Bruno, Misunderstandings about the Tunguska event, shock wave physics, and airbursts have resulted in misinterpretations of evidence at Tall el-Hammam. *Scientific Reports*, (in press) 2025.
- [9] Shoemaker, Eugene M. "Asteroid and comet bombardment of the Earth." *IN: Annual review of earth and planetary sciences. Volume 11 (A83-33477 14-42). Palo Alto, CA, Annual Reviews, Inc., 1983, p. 461-494.* 11 (1983): 461-494.
- [10] Alvarez, Luis W., et al. "Extraterrestrial cause for the Cretaceous-Tertiary extinction." *Science* 208.4448 (1980): 1095-1108.
- [11] Chapman, Clark R., and David Morrison. "Impacts on the Earth by asteroids and comets: assessing the hazard." *Nature* 367.6458 (1994): 33-40.
- [12] Harris, Alan W., and Paul W. Chodas. "The population of near-earth asteroids revisited and updated." *Icarus* 365 (2021): 114452.
- [13] Boslough M & Crawford D (2008). Low-altitude airbursts and the impact threat. *Int. J. Impact. Engng* 35, 1441-1448.
- [14] Boslough M & Crawford D (1997). Shoemaker-Levy 9 and Plume-forming Collisions on Earth. *Annals NY Acad. Sci*, 822, 236-282.
- [15] Boslough M (2013). Airburst warning and response. *Acta Astronautica* doi:10.1016/j.actaastro.2013.09.00.
- [16] Kresák L (1978). The Tunguska object-A fragment of Comet Encke. *Bulletin of the Astronomical Institutes of Czechoslovakia*, 29, 129-134.
- [17] Longo G et al. (2005). A new unified catalogue and a new map of the 1908 tree fall in the site of the Tunguska Cosmic Body explosion. *Asteroidcomet Hazard-2005*, 222-225.
- [18] Brown P et al. (2010). A meteoroid stream survey using the Canadian Meteor Orbit Radar: II: Identification of minor showers using a 3D wavelet transform. *Icarus*, 207(1), 66-81.
- [19] Farley, K. A., et al. "Geochemical evidence for a comet shower in the late Eocene." *Science* 280.5367 (1998): 1250-1253.
- [20] Schmitz, Birger, Mario Tassinari, and Bernhard Peucker-Ehrenbrink. "A rain of ordinary chondritic meteorites in the early Ordovician." *Earth and Planetary Science Letters* 194.1-2 (2001): 1-15.
- [21] Duennebier F et al. (1976). Meteoroid storms detected on the Moon. *Science*, 192(4243), 1000-1002.
- [22] Spurný P et al. (2017). Discovery of a new branch of the Taurid meteoroid stream as a real source of potentially hazardous bodies. *Astronomy & Astrophysics*, 605, A68.
- [23] Olech A et al. (2016). 2015 Southern Taurid fireballs and asteroids 2005 UR and 2005 TF50. *Monthly Notices of the Royal Astronomical Society*, 461(1), 674-683.
- [24] Olech, A et al. (2017). Enhanced activity of the Southern Taurids in 2005 and 2015. *Monthly Notices of the Royal Astronomical Society*, 469(2), 2077-2088.
- [25] Asher D & Izumi K (1998). Meteor observations in Japan : new implications for a Taurid meteoroid swarm. *Mon. Not. R. Astron. Soc*, 297, 23–27.
- [27] Wiegert, P. et al., "A limit on the mass of the Taurid Swarm at sub-100 meter sizes" (submitted to PSJ), 2025.

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