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2032 and 2036 risk enhancement from NEOs in the Taurid stream: Is there a significant coherent component to impact risk?☆,☆☆

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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 Near Earth objects (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 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 (time-dependent) risk, associated with non-random correlated events, remains. 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. Eyewitness accounts and comparison of airburst models to ground truth suggest that the Tunguska object was a Beta Taurid. The Tunguska event is probably an outlier when compared to the size frequency distributions under stochastic assumptions, but if there is a significant coherent component it may be representative of events that take place far more frequently, and risk assessments may have underestimated the contribution from airbursts. If so, the Earth will experience increased risk from objects this size, peaking in November 2032 and June 2036. We recommend targeted survey campaigns during these hypothetical TRS node crossings to quantify the population, search for potentially hazardous objects, and identify imminent impactors.

1. Introduction

Theoretical calculations by Asher and Clube [1] suggest that the last close approaches, within about 1° absolute mean anomaly difference $|\Delta M|$ were in November 1971 and June 1975 for the hypothetical resonant swarm's 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 of NEOs above about 100 m in the TRS has not yet been shown to be statistically significant.

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In 2019 and 2022, the predicted node crossings were close enough to attempt targeted surveys [3,4], with |ΔM| of 5° and 17°, respectively, based on extrapolation of predicted swarm encounters [1]. Upcoming potential targeted survey opportunities will be 2026 and 2029 (|ΔM| of 18° and 23°, 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 an 18:61 resonance with Earth, so the next set of 1° 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]. This has led to widespread confusion about NEO risk by the public and some journalists and policy makers. Nevertheless, we argue that the TRS hypothesis is testable and should not be dismissed just because it has been invoked in association with unsupported claims from outside the domain of peer reviewed science. The possibility of enhanced risk from an undiscovered population of NEOs in the hypothetical TRS should be taken seriously unless comprehensive targeted surveys demonstrate that there is no significant population.

2. 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

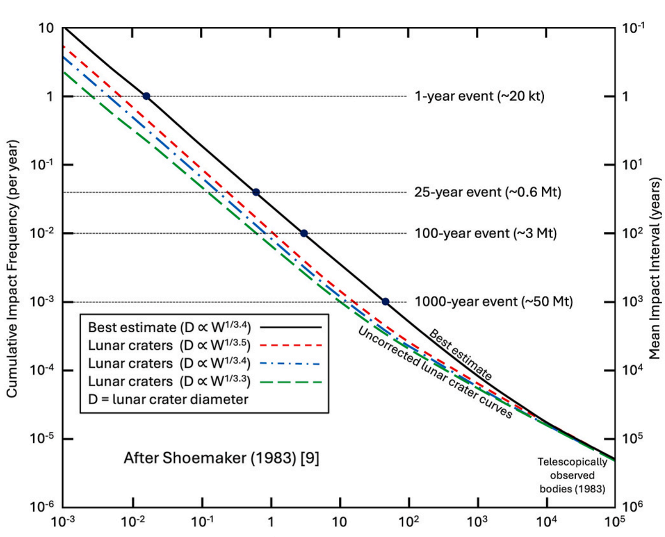

Fig. 1. Cumulative frequency distribution of impact energy for objects colliding with Earth, from Shoemaker [9] Figure 1.

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 for the Tunguska impactor (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 ×/÷2 years; a 30-megaton encounter occurs about every 700 ×/÷2 years. There is a ~12 to ~40% chance that a 12-megaton encounter will occur in an interval of 75 years (the approximate time elapsed since 1908) and a ~5 to ~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.

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 1994, 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] (Fig. 2) 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 exacerbates 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 coherent populations of NEOs that include a significant number of objects that have not been observable, due to their orbital positions, since dedicated NEO surveys started in the 1990s.

3. Coherent risk

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

> 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 (~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 [13]. Napier and Asher [14], who argue in favor of coherent catastrophism and the YDIH, also accept the physics-based airburst models that led to the explanation for 1908 bright nights, and cite Kresak's [15] hypothesis that the Tunguska object was associated with Comet Encke. Further advances in computational modeling of airbursts have created the opportunity to test this association by simulating 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 and 4).

Shoemaker was open to episodes of coherent risk, having posthumously coauthored a 1998 paper suggesting evidence for a comet shower in the late Eocene [18]. Solid evidence for a shower of meteorites from a fragmented asteroid in the early Ordovician was published in 2001 [19]. There is significant evidence for the existence of a Taurid

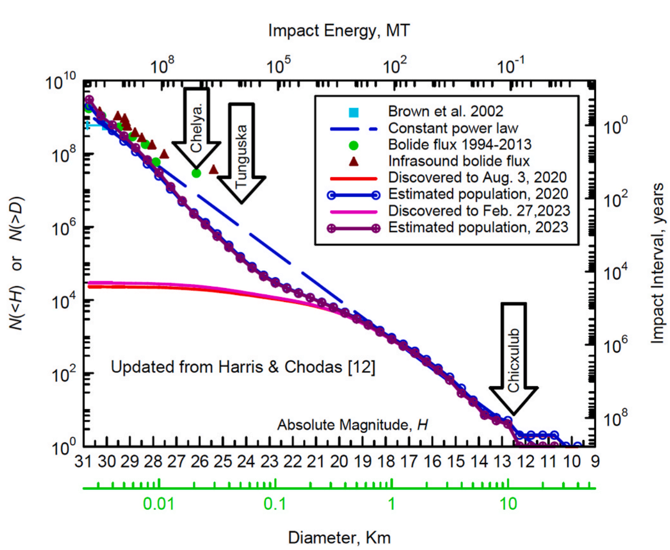

Fig. 2. Cumulative impact frequency distribution and mean impact interval of NEOs as a function of absolute magnitude, with derived estimated values of diameter and impact energy, from Harris and Chodas [12] Figure 8.

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 [20]. 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 [21].

These measurements confirmed with high precision the apparent 7:2 mean motion resonance of the swarm with respect to 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 [22,23], 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 Ref. [1]), ΔM is the encounter offset in units of Mean Anomaly (degrees) relative to the resonant swarm center.

The Tunguska connection to the Beta Taurids has been posited for some time [15] 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.

When the Earth intersects with this stream, the probability of impact is elevated, and so is the probability of discovery by surveys. Trigo-Rodríguez [24] argues that there could be an abundance of small and dark comet fragments in the swarm that are extremely difficult to detect and have not yet been discovered. Because the center of the hypothetical TRC only comes within about 1° mean anomaly relative to the Earth once every 61 years, there have not been any such optimal observational geometries since surveys dedicated to NEO discovery began. This would support Napier and Asher's [20] assertion that "statistical completeness" of surveys for Tunguska-sized objects has not yet been achieved, leaving open the possibility that airburst rates could be significantly underestimated.

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° Mean Anomaly magnitude (Table 1) but yielded no results due to an unscheduled interruption of the dedicated survey time [3,25]. Further observational searches were conducted with CFHT and Zwicky Transient Facility (ZTF) during the 2022 inbound apparition with mean anomaly magnitude of 17°. 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 (29–31 October 2022), by Wiegert et al. [25] during stream geometry depicted in Fig. 5 yielded an upper bound of fewer than 3000 to 30,000 objects brighter than H = 25.6 ± 0.3, corresponding to a diameter of between 34 and 78 m assuming an albedo consistent with comet Encke.

The best upcoming opportunities for dedicated surveys designed to quantify the risk, search for potentially hazardous objects, and identify imminent impactors, are the next close node crossings (ΔM ~ 1°) of the hypothetical TRS in November 2032 and June 2036. These surveys should account for the findings by Tanbakouei et al. [26], who

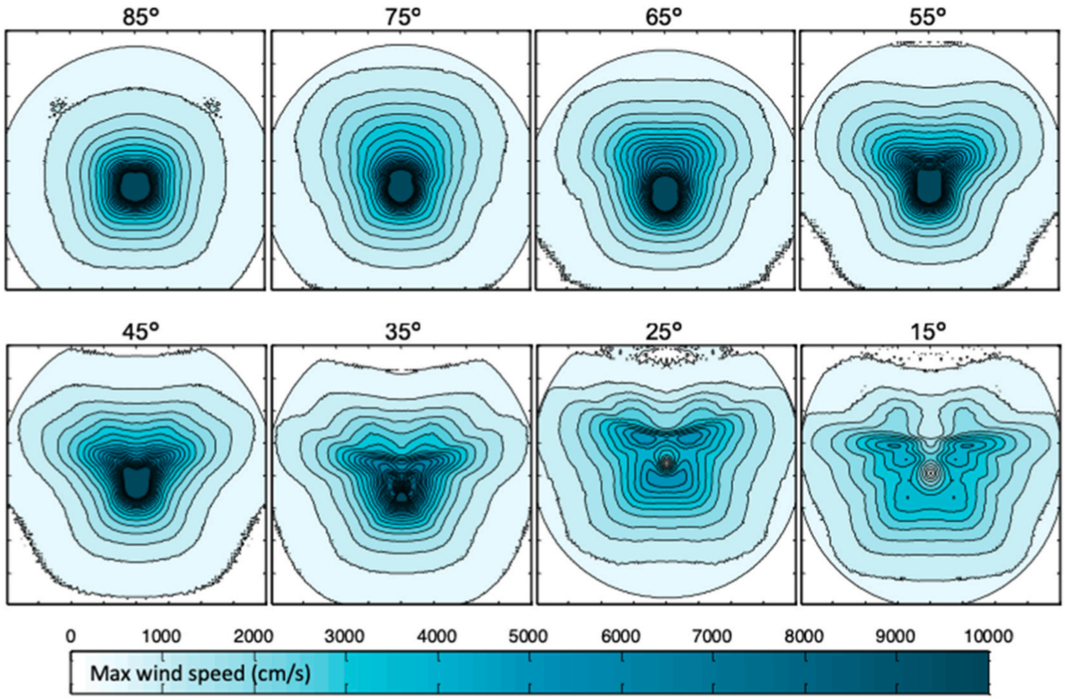

Fig. 3. Series of 8 Mt airburst simulations using 3D hydrocode (CTH) shows that the entry angle (relative to the surface) that best matches the tree-fall observations ranges from 25° to 45° elevation.

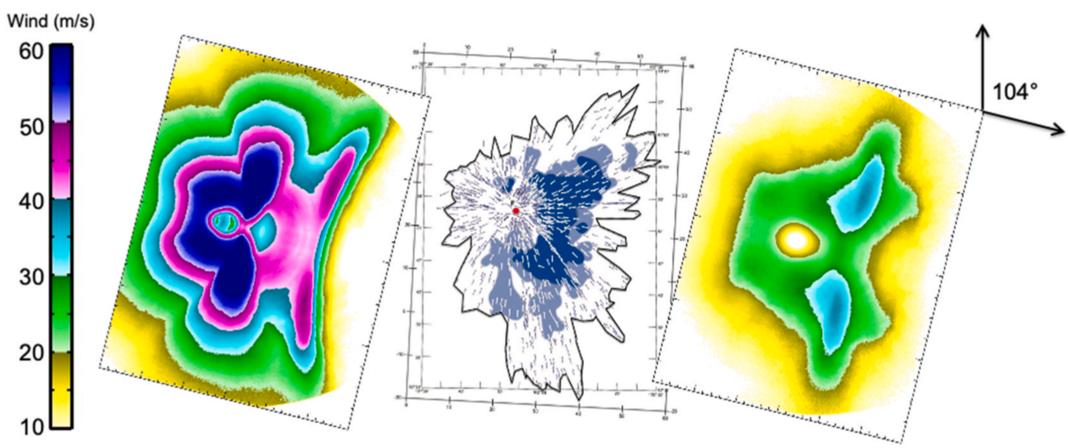

Fig. 4. 3D hydrocode simulations (CTH) provide good match to observed treefall data [16] for 5 Mt body entering at 32° elevation. Orientation of treefall symmetry suggests 104° entry azimuth. According to Brown et al. [17] a Beta Taurid radiant at Tunguska event time and location would imply a 31.5° elevation and 104° azimuth entry. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

determined that the reflectance spectra of dark ungrouped carbonaceous chondrites resemble that of comet Encke. Hazardous, low-albedo objects in the Beta Taurid stream could be embedded within a swarm of small meteoroids, making them difficult to identify in visible wavelengths. This suggests that the proposed survey should also employ infrared telescopes, and that NEO Surveyor should be included as an integral part of the campaign.

4. Coherent catastrophism and dubious claims

Fringe and pseudoscientific claims associated with coherent catastrophism have been promoted by the Comet Research Group (CRG), which receives private funds that are earmarked for "contrarian researchers" to publish alternative science that challenges mainstream research in fields related to astronomy and extraterrestrial visitors [27]. In 2023 the CRG created its own journal, *Airbursts and Cratering Impacts* (A&CI). Most of the editors are members of the CRG, as are authors of most of the papers. According to the A&CI website and list of publications, its purpose is to provide an alternative to the current peer review system by publishing papers that have been rejected or retracted by other journals, are too novel, or run counter to prevailing views on matters such as the criteria that are used to identify impact craters or airburst events, and the physical models used to understand them.

One such paper [28] has made novel and dubious claims about

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

Year (November)	ΔM	Year (June)	ΔM
1910	0	1914	2
1917	23	1921	25
1920	−18	1924	−16
1927	6	1931	7
1930	−36	1934	−34
1934	29	1938	31
1937	−12	1941	−10
1944	11	1948	13
1947	−30	1951	−28
1951	35	1955	37
1954	−6	1958	−5
1961	17	1965	19
1964	−24	1968	−22
1971	−1	1975	1
1978	23	1982	25
1981	−18	1985	−17
1988	5	1992	7
1991	−36	1995	−34
1995	29	1999	30
1998	−13	2002	−11
2005	11	2009	13
2008	−30	2012	−29
2012	35	2016	36
2015	−7	2019	−5
2022	17	2026	18
2025	−25	2029	−23
2032	−1	2036	1

extreme temperatures (>1700 °C) and pressures (5–10 GPa) at Tunguska, citing a retracted CRG paper and other A&CI papers describing attempts to model oblique airbursts with a 2D hydrocode. These papers incorrectly invoke high-temperature, high-pressure "touchdown airbursts," a recently coined term [29] that is synonymous with "Type 2" airbursts defined by Boslough [30] to describe the high-temperature (but not high-pressure) airburst jet that may have formed the Libyan Desert glass [31]. The cited A&CI papers reject established and validated physics-based airburst modeling methods that form the basis for airburst risk assessment by NASA and all three US Department of Energy weapons laboratories [32–34]. This leads to erroneous results that grossly overestimate surface pressures and temperatures. Despite the association of these claims with coherent catastrophism, we argue that the existence of a TRS is a testable hypothesis and that predicted orbital crossings in 2032 and 2036 will provide the next opportunities.

5. 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 less than 120 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 4000 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° mean anomaly on the inbound leg in November 2032, and again on the outbound leg in June 2036. Because there may be a significant or even dominant contribution to the risk from the Taurid resonant swarm, then targeted surveys dedicated to quantification of the population, identification of potentially hazardous objects, and detection of imminent impactors during the passage of the swarm should be implemented.

CRediT authorship contribution statement

Mark Boslough: Writing – original draft, Investigation, Conceptualization. **Peter G. Brown:** Writing – review & editing,

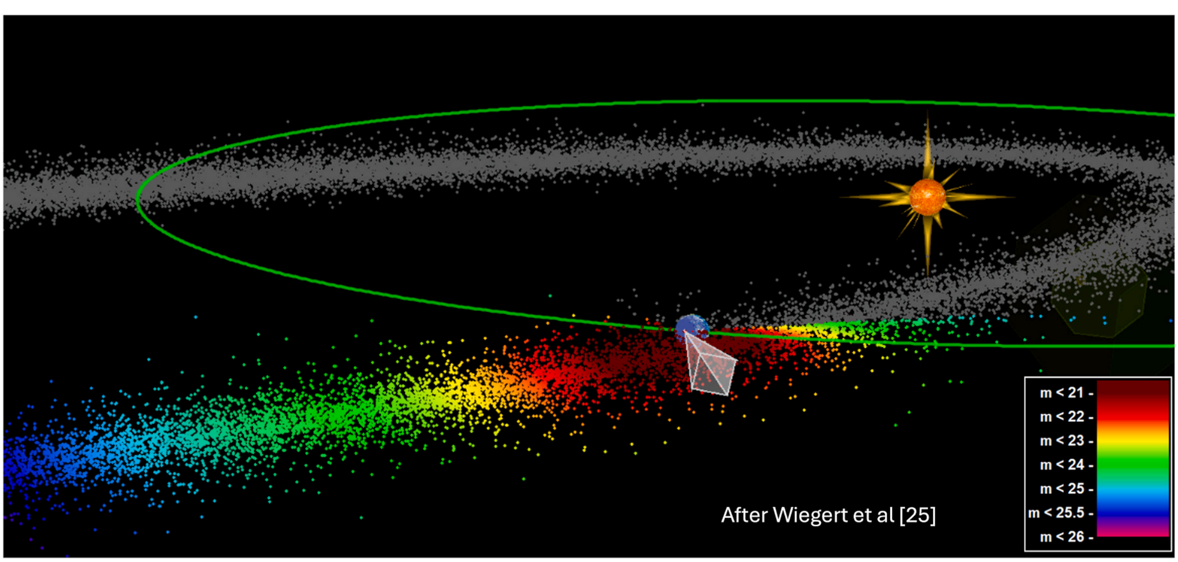

Fig. 5. Taurid stream geometry during the 2022 survey from Wiegert et al. [25] Figure 5. Polyhedron represents the volume of sampled space in a single CFHT image and colors represent the apparent magnitude of Taurids, normalized to a diameter of 100 m, as seen from Earth. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Conceptualization. **David Clark:** Writing – review & editing, Visualization, Software, Conceptualization. **Paul Wiegert:** Writing – review & editing, Visualization, Software, Conceptualization. **Quanzhi Ye:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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