ABSTRACT

The recent publication by Siraj & Loeb (2021; *Nature Scientific Reports* 11, 3803) attempts to revive the debate over whether the Chicxulub impactor was a comet or an asteroid. They calculate that ∼20% of long-period comets impacting Earth will have first been disrupted by passage inside the Sun’s Roche limit, generating thousands of fragments, each the needed size of the Chicxulub impactor. This would increase the impact rate of comets by a factor ∼15, making them as likely to hit the Earth as an asteroid. They also argue that a comet would be a factor of 10 more likely to match the geochemical constraints, which indicate the Chicxulub impactor was carbonaceous chondrite-like. These conclusions are based on misinterpretations of the literature. Siraj & Loeb [1] overestimate the number of fragments produced during tidal disruption of a comet: tens of fragments are produced, not thousands. They also conflate ‘carbonaceous chondrite’ with specific types of carbonaceous chondrite, and ignore the evidence of iridium, making comets seem more likely than asteroids to match the Chicxulub impactor, when in fact they likely can be ruled out. Rather than a comet, an asteroidal impactor similar to CM or CR carbonaceous chondrites is strongly favored.

Introduction

Since the discovery of Ir in the clay layer at the K-Pg boundary [2], scientists have sought to constrain the origin of the extraterrestrial impactor that triggered the end-Cretaceous mass extinction of the non-avian dinosaurs and other species. While the first proposal was for an asteroid [2], for a while some theories invoked a cometary impactor to explain perceived periodicities in mass extinctions [3]. Such models have long been disfavored by the mass of Ir in the layer, inferred to be 2.0 − 2.8 × 10^{11} g [4]. The size of Chicxulub crater leads to an estimated asteroid impactor diameter, \( D \approx 10 \) km [5, 6]. For a cometary impactor this decreases to \( D \approx 7 \) km due to the higher impact speed [5]. A carbonaceous chondrite-like asteroid of this size would likely deliver \( \approx 2.3 \times 10^{11} \) g or Ir [5], in the center of the estimated mass range of the global Ir layer; but a comet would only deliver \( \approx 0.1 \times 10^{11} \) g, because it is smaller and mostly ice. Against this backdrop, Siraj & Loeb [1] have argued in favor of a comet over an asteroid, based on dynamical and geochemical evidence. Here we demonstrate that their arguments are based on misinterpretations of the literature, and that an asteroid is in fact highly favored over a comet.

Geochemical Arguments

Siraj & Loeb [1] cite good evidence that the Chicxulub impactor was carbonaceous chondrite-like, but then assert that 100% of comets satisfy this constraint but only 10% of asteroids do. This assertion conflates carbonaceous chondrites with specific types (CB, CH, CI, CM, CO, CR, CV) of carbonaceous chondrites. It underestimates the fraction of asteroids that match the Chicxulub impactor’s composition, and/or overestimates the fraction of comets that would.

Siraj & Loeb [1], citing Bottke et al. [7], claim only 30% of asteroids are C-type (spectrally resembling carbonaceous chondrites) and appear to imply that only 40% of carbonaceous chondrites are the specific type CM associated with the impactor. In fact the fraction of asteroids that are C-type is \( > 50\% \) [8]. As well, the Chicxulub impactor could be CM- or CR-like. Siraj & Loeb [1] cite evidence from a fossil meteorite in the K-Pg clay layer, which demands the impactor be CV, CO, CR, or possibly CM, but not CI [9]. They also cite evidence from the \( \varepsilon^{54}\text{Cr} \) isotopic anomaly in the K-Pg clay layer, which argues the impactor was CM (and CR, CH, and CB have the same \( \varepsilon^{54}\text{Cr} \)), but argues against CV, CO, and CI [10]. The authors could have cited equally strong arguments from platinum-group element patterns, which favor CM or CO (and allow
CR), but rule out CI [11]. The composition of the Chicxulub impactor is a match to either CM or CR chondrites. Siraj & Loeb [1] argue that CM chondrites comprise a fraction ≈ 40% of all carbonaceous chondrites, based on statistics of intact falls; but a larger fraction of C-type asteroids may match CM or CR chondrites. At a minimum, ≈ 50% of asteroids are carbonaceous chondrite-like, and > 20% of asteroids striking Earth match the specific composition of the Chicxulub impactor.

Siraj & Loeb [1] claim 100% of comets are carbonaceous chondrite-like, which may be loosely true; but comets are not definitively associated with any particular subtype of carbonaceous chondrite, but are most strongly associated with carbonaceous chondrites of type CI, based on their low albedos, friability, lack of chondrules, presence of anhydrous silicates, and low impact rate on Earth [12]. A comet-like origin has been argued for CI chondrites like Orgueil [13]. None of the lines of geochemical evidence above is consistent with CI chondrites, indicating that while 100% of comets may be carbonaceous chondrite-like, possibly 0% of them match the specific composition of the Chicxulub impactor in detail.

Siraj & Loeb [1] applied a double standard to the geochemical evidence. If the impactor must only be carbonaceous chondrite-like, then comets are more likely (for a given impact rate) by a factor of 2, not 10. If the impactor must match a CM or CR composition, then > 20% of asteroids provide a match, but no comets do. The mass of Ir in the clay layer likewise is a match to an asteroidal impactor, but not a comet.

**Dynamical Arguments**

Siraj & Loeb [1] downplay the frequency with which asteroids impact Earth, and overestimate the likelihood of a comet impact. The authors state that the Chicxulub impact was the single largest impact in the last 250 Myr, and that asteroids with $D = 10$ km should impact Earth with mean rate once per ~ 350 Myr. Therefore by their own numbers the probability of a $D > 10$ km asteroid impacting Earth in the last 250 Myr is > 50%. Whatever the probability of a comet impact, an asteroid impact is a probable event.

The main point of Siraj & Loeb [1] is that a significant fraction, ~ 20%, of long-period comets (LPCs) impacting the Earth will have first passed through the Sun’s Roche limit and fragmented into a number, $N$, of smaller comets, potentially increasing the probability one will strike Earth. A comet $N$ times more massive than the final Chicxulub impactor is rarer than an undisrupted LPC with the size of the Chicxulub impactor, by a factor of $τ = (N^{1/3})^{1−q}$, where $q ≈ 2.0 − 2.7$; but because there are more fragments, this would increase the rate of Chicxulub-scale impactors by a factor $≈ 0.2 × N × N^{(1−q)/3}$, which is ≈ 15 for $q = 2$ and $N = 630$ (equivalent to a 60 km-diameter comet breaking up into ones with diameter 7 km). The authors state that undisrupted LPCs the size of the Chicxulub impactor ($D = 7$ km) are expected to impact Earth once every 3.8 - 11 Gyr, so only if $N ≈ 10^3$, enhancing the fluxes by factors > 15, is the collision timescale ≈ 250 Myr and comparable to asteroids.

Despite its importance, the choice of $N ≈ 630$ appears unjustified. Tidal disruption of comets like Shoemaker-Levy 9, and crater chains on Jupiter’s moons, suggest a value closer to ~ 20. The analytical treatment of Hahn & Rettig [14] shows the number of fragments generated is fixed during the encounter, by the relative timescales of spreading and gravitational contraction, which are functions of the comet’s density, $ρ_c$, and its perihelion distance, $r_0$. The contraction timescale, $t_{contr}$, in units of the encounter timescale, $τ = (Gρ_c)^{-1/2}$, is $t_{contr}/τ ≈ 0.94(ρ_c/ρ_0)^{1/2}N^{1/2}$, where $ρ_c = (1M_⊙)/r_0^3$. The spreading timescale in units of the encounter timescale is found by numerical simulation and appears to be $t_{spread}/τ ≈ 0.7N^{0.85}$, assuming the dimensionless treatment applies to the Sun as well as Jupiter. A disrupted comet coalesces into fragments when these timescales are equal, which is when $N ≈ 2.3(ρ_c/ρ_0)^{1.43}$. The closer to the Sun the comet penetrates, the more fragments are produced, but the minimum value of $r_0$, $1R_⊙$, corresponds to $ρ_c = 5.9g cm^{-3}$. Assuming the authors’ $ρ_0 = 0.7g cm^{-3}$, the maximum number of fragments that can be produced by tidal disruption is ~ 50, for comets unrealistically skimming the Sun’s photosphere. Assuming a more typical $r_0 ≈ 0.7 × $ the Roche limit, $N ≈ 12$ is more likely. That this is similar to the number of fragments produced in the tidal disruption of Shoemaker-Levy 9 is unsurprising since Jupiter and the Sun are of similar density. The estimate $N ≈ 10^3$ made by Siraj & Loeb [1] appears to be based on a misinterpretation of Hahn & Rettig [14], somehow setting $N$ equal to $t/τ$, where $t$ is the time for the fragments to reach Earth.

In addition, applying the formulation of Hahn & Rettig [14] to the case of a $D = 60$ km comet rounding the Sun, the length of the debris chain would be roughly 50 Earth diameters. Supposing $N ≈ 10^3$ fragments were generated and distributed over this length, the Earth would have collided with ~ 20 of them. This would lower the effective number of fragments to a maximum of ~ 50, leading to very little enhancement of the probability of a comet impact. It also would demand the Chicxulub impact be one of a chain of ~ 20 craters on Earth, which is not observed.

**Summary**

Siraj & Loeb [1] make a valid point that a Chicxulub-scale cometary impactor ($D = 7$ km) may be not quite as uncommon as previously thought, because some fraction of comets may be tidally disrupted by passage within the Sun’s Roche limit. Similar ideas were expressed by Bailey et al. [15]. But even setting $q = 2$ and $r_0 = 1R_⊙$, so that $N = 50$, the enhancement in
flux is only a factor < 4; and using the more likely N = 12, the enhancement is only a factor of 2. The mean timescale for an impact with a Chicxulub-scale comet is most likely > 2 Gyr, while the mean timescale with an asteroid remains ~ 350 Myr.

Siraj & Loeb [1] applied a double standard to the geochemical evidence. If only a loose match to a carbonaceous chondrite is demanded, then comets are only a factor of 2, not 10, more likely than asteroids (for the same impact rate). If it is demanded that the impactors match a CM or CR carbonaceous chondrite composition, then > 20% of asteroids, but possibly ~ 0% of comets, are a match. As well, Siraj & Loeb [1] cite Alvarez et al. [2] but ignore the evidence from the iridium in the K-Pg clay layer that is the point of that paper, which favors an asteroidal impactor but strongly disfavors a comet, which only supplies about 4% as much iridium as an asteroid [5].

There is a > 50% probability a D = 10 km asteroid would have hit the Earth in the last 250 Myr. Among Earth-crossing asteroids, ≈ 50% are C-type, associated with carbonaceous chondrites. At least 40% of C-type asteroids, possibly more, will be of the type CM or CR that match the Chicxulub impactor. In contrast, even after including tidal disruption, the mean timescale for impacts by D = 7 km comets is > 2 Gyr, in tension with the recency of the Chicxulub impact, as there is only a ~ 10% probability of such an impact in the last 250 Myr. Because of the flaws in their interpretation of the literature, the dynamical and geochemical arguments presented by Siraj & Loeb [1] do not change the consensus that an asteroid, not a comet, struck the Earth 66 Myr ago.

References
1. Siraj, A. & Loeb, A. Breakup of a long-period comet as the origin of the dinosaur extinction. Sci. Reports 11, 3803, DOI: 10.1038/s41598-021-82320-2 (2021). 2102.06785.
2. Alvarez, L. W., Alvarez, W., Asaro, F. & Michel, H. V. Extraterrestrial Cause for the Cretaceous-Tertiary Extinction. Science 208, 1095–1108, DOI: 10.1126/science.208.4448.1095 (1980).
3. Rampino, M. R. & Stothers, R. B. Terrestrial mass extinctions, cometary impacts and the Sun’s motion perpendicular to the galactic plane. Nature 308, 709–712, DOI: 10.1038/308709a0 (1984).
4. Artemieva, N. & Morgan, J. Modeling the formation of the K-Pg boundary layer. Icarus 201, 768–780, DOI: 10.1016/j.icarus.2009.01.021 (2009).
5. Brittan, J. Iridium at the K/T boundary - the impact strikes back. Astron. Geophys. 38, 19–21 (1997).
6. Ivanov, B. A. Numerical Modeling of the Largest Terrestrial Meteorite Craters. Sol. Syst. Res. 39, 381–409, DOI: 10.1007/s11208-005-0051-0 (2005).
7. Bottke, W. F., Vokrouhlický, D. & Nesvorný, D. An asteroid breakup 160Myr ago as the probable source of the K/T impactor. Nature 449, 48–53, DOI: 10.1038/nature06070 (2007).
8. Morbidelli, A. et al. Debiased albedo distribution for Near Earth Objects. Icarus 340, 113631, DOI: 10.1016/j.icarus.2020.113631 (2020). 2001.03550.
9. Kyte, F. T. A meteorite from the Cretaceous/Tertiary boundary. Nature 396, 237–239, DOI: 10.1038/24322 (1998).
10. Trinquier, A., Birck, J.-L. & Jean Allègre, C. The nature of the KT impactor. A 54Cr reappraisal. Earth Planet. Sci. Lett. 241, 780–788, DOI: 10.1016/j.epsl.2005.11.006 (2006).
11. Goderis, S. et al. Reevaluation of siderophile element abundances and ratios across the Cretaceous-Paleogene (K-Pg) boundary: Implications for the nature of the projectile. Geochimica et Cosmochimica Acta 120, 417–446, DOI: 10.1016/j.gca.2013.06.010 (2013).
12. Campins, H. & Swindle, T. D. Expected characteristics of cometary meteorites. Meteorit. Planet. Sci. 33, 1201–1211, DOI: 10.1111/j.1945-5100.1998.tb01305.x (1998).
13. Gounelle, M., Spurný, P. & Bland, P. A. The orbit and atmospheric trajectory of the Orgueil meteorite from historical records. Meteorit. Planet. Sci. 41, 135–150, DOI: 10.1111/j.1945-5100.2006.tb00198.x (2006).
14. Hahn, J. M. & Rettig, T. W. Tidal disruption of strengthless rubble piles - a dimensional analysis. Planet. Space Sci. 46, 1677–1682, DOI: 10.1016/S0032-0633(98)00055-5 (1998).
15. Bailey, M. E., Chambers, J. E. & Hahn, G. Origin of sungrazers - A frequent cometary end-state. Astron. Astrophys. 257, 315–322 (1992).
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S.D. led the writing of this manuscript. A.J., J.N., and A.A. contributed ideas. All authors reviewed the manuscript.

Additional information
The authors declare no competing interests.