The breakup of a long-period comet is not a likely match to the Chicxulub impactor

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Since the discovery of Ir in the clay layer at the K-Pg boundary3, 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 asteroid1, for a while some theories invoked a cometary impactor to explain perceived periodicities in mass extinctions2. Such models have long been disfavored by the near-Earth asteroids are carbonaceous chondrite-like, and asteroid impactor diameter, CR-like. Siraj and Loeb7 cite evidence from a fossil meteorite in well, the Chicxulub impactor could be CM or CR chondrites. At a minimum, for the same impact energy4. Although it is increasingly recognized that a continuum exists between comets and asteroids, 'comets' are considered to be more ice-rich (estimates for 67P/Churyumov-Gerasimenko are about 20%), implying lower Ir contents per impactor mass. A carbonaceous chondrite-like asteroid of the appropriate size would likely deliver \(\approx 2.3 \times 10^{11} \text{ g}\) of Ir4, in the center of the estimated mass range of the global Ir layer; but a comet would only deliver \(\approx 0.1 \times 10^{11} \text{ g}\), because it would be less massive. Although these conclusions are long standing, Siraj and Loeb7 have recently argued anew 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 still highly favored over a comet.

Geochemical arguments

Siraj and Loeb7 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 and Loeb7, citing Bottke et al.8, 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 near-Earth asteroids that are C-type is \(\sim 40-50\%\). As well, the Chicxulub impactor could be CM- or CR-like. Siraj and Loeb7 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 CI11. 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 CI11. The authors could have cited equally strong arguments from platinum-group element patterns, which favor CM or CO (and allow CR), but rule out CI11. The composition of the Chicxulub impactor is a match to either CM or CR chondrites. Siraj and Loeb7 argue that CM chondrites comprise a fraction \(\sim 40\%\) 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, \(\sim 40-50\%\) of near-Earth asteroids are carbonaceous chondrite-like, and > 20% of asteroids striking Earth match the specific composition of the Chicxulub impactor.

Siraj and Loeb7 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. They are most strongly associated with carbonaceous chondrites of type CI, based on their low albedo, friability, lack of chondrules, presence of anhydrous silicates, and low impact rate on Earth13. A comet-like origin has been argued for CI chondrites like Orgueil13, and indeed the reflectance spectrum of the refractory crust of 67P/Churyumov-Gerasimenko is most similar to the insoluble organic material of Orgueil13. There nevertheless remain significant differences between 67P and CI chondrites and carbonaceous chondrites in general13, and comets do not need to conform to any carbonaceous chondrite; but of them, they most closely resemble CI chondrites. Notably, none of the lines of

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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.

The net effect is that Siraj and Loeb applied differing standards to the geochemical evidence for asteroids and comets. If the impactor must simply 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 specifically match a CM or CR composition, then > 20% of asteroids provide a match, but perhaps no comets do.

Crucially, the mass of Ir in the clay layer likewise is a match to an asteroidal impactor, but not a comet.

**Dynamical arguments**

Siraj and Loeb\(^7\) 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 the Earth with mean rate once per \(\sim 350\) 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 impactor is a probable event.

The main point of Siraj and Loeb\(^7\) is that a significant fraction, \(\sim 20\%\), 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 \(\left(\frac{N^{1/3}}{q}\right)^4\), where \(q \approx 2.0 - 2.7\); but because there are more fragments, this would increase the rate of Chicxulub-scale impactors by a factor \(\approx 0.2 \times N \times N^{(1-\rho_\odot)}\), which is \(\approx 15\) 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 \(N \sim 10^3\), enhancing the fluxes by factors > 15, is the collision timescale < 250 Myr and comparable to asteroids.

Despite its central importance, the choice of \(N \approx 630\) appears unjustified. The analytical treatment of Hahn & Rettig\(^6\) 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, \(\rho_0\), and its perihelion distance, \(r_0\). The spreading timescale, \(t_{\text{spread}}\), in units of the encounter timescale, \(\tau = (G\rho_0)^{-1/2}\), is \(t_{\text{spread}} < 250\) Myr and comparable to asteroids. Whatever \(t_{\text{spread}}\), the collision timescale, \(t_{\text{coll}}\), is \(t_{\text{coll}} = t_{\text{spread}} < 250\) Myr and comparable to asteroids. If the impactor must simply be carbonaceous chondrite-like, 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 \(\sim 0\%\) of comets, are a match. As well, Siraj and Loeb\(^1\) cite Alvarez et al.\(^1\) but do not even discuss 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\(^4\).

**Summary**

Siraj and Loeb\(^7\) 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 30 years ago by Bailey et al.\(^23\). But even setting \(q = 2\) and \(r_0 = 1R_\odot\), 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 \(\sim 350\) Myr.

Siraj and Loeb\(^7\) effectively applied different standards to the geochemical evidence for comets and asteroids. 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 \(\sim 0\%\) of comets, are a match. As well, Siraj and Loeb\(^1\) cite Alvarez et al.\(^1\) but do not even discuss 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\(^4\).
There is a > 50% probability a $\Delta = 10$ km asteroid would have hit the Earth in the last 250 Myr. Among Earth-crossing asteroids, $\sim 40$–50% are C-type, associated with carbonaceous chondrites. At least 40% of C-type asteroids, possibly even 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 $\Delta = 7$ km comets is $\sim 2$ Gyr, in tension with the recency of the Chicxulub impact, as there is only a $\sim 10\%$ 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 and Loeb do not change the consensus that an asteroid, not a comet, struck the Earth 66 Myr ago.

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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.

Competing interests
The authors declare no competing interests.

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