recent paper by Siraj & Loeb (2021) entitled “Breakup of a long-period comet as the origin of the dinosaur extinction” attempts to revive the perennial debate about what type of body hit the Earth 66 million years ago, triggering the end-Cretaceous extinction. Here we critique the paper and assess the evidence it presents. To consider a comet more likely than an asteroid requires extreme assumptions about how comets fragment, conflation of carbonaceous chondrites with specific types of carbonaceous chondrites, and a blind eye to the evidence of the iridium layer.

The discovery by Alvarez et al. (1980) of significant iridium (Ir) in the global K–Pg (Cretaceous–Paleogene) boundary clay layer at Gubbio, Italy, has revolutionized our understanding of how the geology of Earth is affected by extraplanetary objects. Further work demonstrated that the Ir layer followed distinct and predictable thickness and composition from the K–Pg boundary around 66 million years ago (Alvarez et al. 1980), but it wasn’t until later that the impact theory was linked with Chicxulub (Hildebrand et al. 1991). The approximate extent of the Chicxulub crater is marked here by the dotted circle, over the northern coast of the Yucatán Peninsula in Mexico. The crater is estimated to be about 150 km wide, but is now buried beneath several hundred metres of sediment. Its initial discovery (Penfield & Camargo 1981) occurred around the same time as the hypothesis that Earth experienced a huge impact at the K–Pg boundary around 66 million years ago (Alvarez et al. 1980), but it wasn’t until later that the impact theory was linked with Chicxulub (Hildebrand et al. 1991).

A perennial debate about what type of body hit the Earth 66 million years ago, triggering the end-Cretaceous extinction. Here we critique the paper and assess the evidence it presents. To consider a comet more likely than an asteroid requires extreme assumptions about how comets fragment, conflation of carbonaceous chondrites with specific types of carbonaceous chondrites, and a blind eye to the evidence of the iridium layer.

The Chicxulub impactor: comet or asteroid?

The Chicxulub impactor: comet or asteroid?

Steve Desch, Alan Jackson, Jessica Noviello and Ariel Anbar assess the evidence for what type of object caused the end-Cretaceous extinction and suggest best practices for writing and reviewing interdisciplinary papers.
deliver $\approx 2.3 \times 10^{10}$ g of Ir, very satisfactorily matching the requirement. In contrast, a $D=7$ km comet is estimated to deliver only $\approx 0.1 \times 10^{10}$ g of Ir, because it is smaller and half ice. On this basis alone, an asteroid is strongly favoured as the impactor, and a comet is practically ruled out.

Siraj & Loeb ignored the Ir constraint, but do consider that the Chicxulub impactor had a composition like carbonaceous chondrites. In doing so, however, they missed the distinctions between different types of carbonaceous chondrites. Meteoritists identify several such types: CV, CK, CO, CR, CM and CI, plus the unusual CH and CB, each type having slightly different chemical and isotopic composition. When considering an asteroid impactor, Siraj & Loeb took the fraction of Earth-crossing MBAs that are C-type (spectrally associated with carbonaceous chondrites) to be $\approx 30\%$, with $\approx 40\%$ of those being CM-like (Bottke et al. 2007), concluding that only $\approx 10\%$ of MBAs could provide a match to the impactor. Meanwhile, they considered 100% of comets to match carbonaceous chondrites, and did not make further distinctions. This double standard made comets appear $\approx 10\times$ more likely than asteroids, but comets are at most a factor of $\approx 2$ times more likely to be carbonaceous chondrite. Moreover, a careful consideration reveals that the Chicxulub impactor was a particular type of carbonaceous chondrite not matched by comets at all.

Several lines of evidence point to the Chicxulub impactor being either a CM or CR carbonaceous chondrite. The first (noted by Siraj & Loeb) is a fossil meteorite recovered from marine sediments deposited at K–Pg time in the North Pacific Ocean, which is very likely to sample the impactor itself (Kyte 1998). Based on a metal and sulphide content $\approx 4\%$ by volume, an inferred metal abundance $\approx 30\%$ to $60\%$ by volume, and the presence of $\approx 200 \mu m$ inclusions, Kyte (1998) favoured a carbonaceous chondrite of type CV, CO or CR, and allowed for the possibility of CM type despite their lower abundances of opaque minerals. In contrast, CI chondrites have essentially no metal, are $\approx 99\%$ by volume matrix, and can be excluded.

The second line of evidence (also cited by Siraj & Loeb) is the excess of the isotope $^{54}$Cr (up to $\epsilon^{54}$Cr $=+1.0$) that has been measured in the marine clay layer (Shukolyukov & Lugmair 1998, Trinquier et al. 2006). This excess is matched only by certain types of carbonaceous chondrites. CV, CO or CR chondrites have $\epsilon^{54}$Cr $<1.0$, too low to cause this anomaly. Trinquier et al. (2006) calculate the implied mixing fractions of extraterrestrial material in the marine clay layer are roughly 6–19% if it is CM chondrite-like (CR, CH and CB would be similar), and 1.7–2.6% if it is CI chondrite-like. The mixing ratios of impactor to terrestrial materials in the marine clay layer are estimated by other means to be 6.5±2.7% (Kyte et al. 1980) or 7.9±3.8% (Ganapathy 1980), so CM (or CR) chondrites provide a very satisfactory match. A CI composition can be ruled out at the $\approx 99\%$ probability level.

A third line of evidence (not considered by Siraj & Loeb) comes from platinum-group elements (PGEs) in the marine clay layer. The ratios between Pt, Ir, Rh, Ru and Pd, especially Rh/Ir ratios, strongly favour carbonaceous chondrites of type CM or CO (Goderis et al. 2013). Sufficient data are lacking, but CR chondrites appear consistent as well. But CI chondrites are ruled out by the PGE evidence (Goderis et al. 2013).

A fourth line of evidence (also not considered by Siraj & Loeb) comes from abundances of extraterrestrial amino acids in the K–Pg clay layer. Zhao & Bada (1989) measured the abundances of isovaline and $\alpha$-amino-isobutyric acid (AIB), two amino acids rare on Earth but common in carbonaceous chondrites. The AIB/Ir mass ratios were inferred to be $\approx 100$ in the clay layer, roughly comparable to the levels found in CM2 and CR2 chondrites, which have $\approx 700$ ppb Ir (Wasson & Kalleney 1988) and $\approx 5000–50000$ ppb AIB (Glavin et al. 2010). The AIB/isovaline ratios in the clay layer, $\approx 2$–4 (Zhao & Bada 1989), also are roughly consistent with the ratios, $\approx 2.0$, in CM2 and CR2 chondrites (Glavin et al. 2010). Significantly, the AIB abundances of CI chondrites are $<1000$ ppb (Glavin et al. 2010), and the total amino acid contents of CV, CK, CO, CB chondrites are $<1000$ ppb (Elisa et al. 2016), so all other carbonaceous chondrites (except CM) can be excluded.

### Meteores

These lines of evidence are reviewed in table 1. The PGE and amino acid data, combined with the $\epsilon^{54}$Cr and fossil meteorite evidence, point strongly to the Chicxulub impactor having a carbonaceous chondrite composition of type CM or CR in particular. All other types, especially CI chondrites, can be ruled out. At first this constraint would seem very restrictive: CM and CR chondrites comprise only a few percent of intact meteorite falls. But intact falls represent a very small fraction, $\ll 1\%$, of the total meteoritic material striking the Earth (Bland 1996). Micrometeorites collected in Antarctica are overwhelmingly associated with CM and CR chondrites (Engrand & Maurette 1998). All this suggests that CM and CR chondrites are perhaps more representative of asteroids reaching Earth but are simply underrepresented among intact meteorite falls. At any rate, the $\approx 40\%$ of carbonaceous chondrites that are of type CM should be considered a reasonable match to the Chicxulub impactor. The fraction of Earth-crossing asteroids that are C-type is closer to 50\% (Morbidelli et al. 2020), so the fraction of MBAs striking Earth that would match the impactor’s composition is not $\approx 10\%$, but in fact at least 20\%.

While Siraj & Loeb demand an asteroid match to a CM composition, they only demand that a comet match a carbonaceous chondrite composition generally, and point to the Stardust comet return sample having a “carbonaceous chondrite” composition (Zolensky et al. 2008) to assert that 100% of comets do. But comets are only reasonably a match to CI chondrites. As reviewed by Campins & Swindle (1998), cometary materials must be identified with a meteorite type that is rare ($<10$ in our collections), dark, weak and friable, with low density, containing anhydrous silicates, and no chondrules. Almost all of these criteria are uniquely met by CI chondrites; in contrast, all other known carbonaceous chondrites, including CM, violate most of these constraints. Gounelle et al. (2006) made a strong case that the CI chondrite Orgeuil, whose fall was observed in 1864, originated from a Jupiter family comet, and that CI chondrites may represent cometary materials generally. The protoplanetary disc model of Desch et al. (2018) predicts that the known carbonaceous chondrites formed roughly at Jupiter’s orbit, except for CI chondrites, which must originate beyond Saturn’s orbit, where comets are expected to form. In truth, comets probably sample a mix of both known and unknown carbonaceous chondrites; but if

| Table 1 Comparison of carbonaceous chondrite types |
|--------------------------------------------------|
| constraint | CV | CK | CO | CH | CB | CM | CR | CI |
| fossil meteorite | yes | ? | yes | no | no | yes | yes | no |
| $\epsilon^{54}$Cr | no | no | yes | yes | yes | yes | yes | no |
| PGE | no | no | yes | yes | no | yes | yes | no |
| amino acids | no | no | no | no | no | no | yes | no |

Comparison of different carbonaceous chondrite types with geochemical and other constraints from the fossil meteorite, the $\epsilon^{54}$Cr anomaly, platinum-group elements, and amino acid abundances in the K–Pg clay layer. Only CM and CR chondrites provide a match.
one had to select a known type to represent comets, it would only be CI, and would not be CM.

If the Chicxulub impactor is identified only with carbonaceous chondrites, then ~50% of MBAs and perhaps 100% of LPCs would qualify as a match. For comparable impact rates, a comet would be approximately twice as likely as an asteroid to be the impactor. But if the Chicxulub impactor must be identified with a CM or CR (but not CI) chondrite, and comets are identified with a CI (but not CM or CR) chondrite, then ~20% of MBAs but ~0% of LPCs would qualify as a match. Siraj & Loeb only concluded that comets were approximately 10 times more likely than asteroids because they conflated carbonaceous chondrites with specific meteorite types, and ignored the Ir evidence.

### Impact rates

Beyond the geochemical evidence, Siraj & Loeb calculated the impact rates of comets to suggest they would be plausible impactors where asteroids would not be. The case against asteroids is weak. They claimed the background impact rates of MBAs are too low to explain the Chicxulub impact event, and can be dismissed. Yet their first paragraph states both that Chicxulub was the largest impact in the last 250 Myr, and that impacts of MBAs of its size (diameter $D > 10$ km) should occur with mean interval $t_{MBAs} = 350$ Myr. Thus the likelihood of a Chicxulub-scale asteroid impact over the last 250 Myr is 50%. Just as comet disruption could increase the impact rate, so could collisional disruption of a larger asteroid. Bottke et al. (2007) hypothesized that the break-up of the asteroid 298 Baptistina might have enhanced the MBA impact flux by a factor of 2 over the last 100 Myr. Siraj & Loeb cite relevant literature to dispute this, but this is a straw man argument. Impact by an asteroid is plausible, even likely, even if Baptistina is an unlikely source.

In contrast, collision with a cometary impactor is only probable if it is a fragment from a larger LPC. The impact rate of Chicxulub-scale comets must be extrapolated from the numbers of smaller comets, but assuming a cumulative size distribution power law with index $q = 2$, a comet with diameter $D = 7$ km strikes the Earth with mean interval 3800 Myr, making the probability <7% that one has impacted in the last 250 Myr. To make the impact more probable, Siraj & Loeb calculated that 20% of LPCs hitting Earth would first pass through the Sun's Roche limit and be tidally disrupted. They cited the evidence of Shoemaker–Levy 9 (Walsh 2018) and crater chains on Ganymede and Callisto (Schenk et al. 1996) to argue that all LPCs should disrupt into a number $N$ of equal-sized fragments, increasing the probability of a fragment impacting, by a factor $E = 0.2 \times N \times (D/7$ km)$^{-3}$. However, only those progenitor comets with diameter $D > N^{1/3} (7$ km) would yield a Chicxulub-scale impact, so the enhancement factor is $E = 0.2 \times N \times (N^{1/3})^{-3}$. The mean interval between impacts by comet fragments capable of making a Chicxulub-sized crater is then $t_{frag} = 3800$ Myr/E.

Assuming the existence of sufficiently large progenitor comets, the impact rate of fragments is maximized by assuming the largest possible value of $N$. Siraj & Loeb implicitly assumed a value $N = 630$, yielding $E = 15$, so that $t_{frag} = 260$ Myr. This value of $N$ was poorly justified and appears to have been chosen so that a typical size of comet, $D = 60$ km, would break up into fragments with diameter 7 km, just sufficient to create the largest possible number of Chicxulub-scale impacts. Even so, the impact rate of comet fragments (1 every 260 Myr) would not significantly exceed that of asteroids (1 every 350 Myr). However, the examples of Shoemaker–Levy 9 and the crater chains strongly suggest that comets typically are tidally disrupted into a much smaller number of fragments.

### Assessment of probabilities

We calculate the relative probability of the Chicxulub impactor being a comet or an asteroid, parameterizing the uncertain value of $N$. The relative probability of a comet impacting is $P(\text{comet}) = [1 + t_{frag}/(260)$ Myr$]^{-1}$, and of an asteroid is $P(\text{asteroid}) = 1 - P(\text{comet})$. Without fragmentation, $P(\text{comet}) = 8%$. For a plausible value, $N = 20$, the relative probability of a comet is 12% if $q = 2$, the slope of the size–frequency distribution for dynamically hot Kuiper belt objects (KBOs); or 22% if $q = 2.9$, appropriate for dynamically cold KBOs (Fraser et al. 2014). Only if $q = 2$ and $N > 600$ would the probability of a comet become comparable to the probability of an asteroid.

We then use Bayes’s theorem to combine the above impact rate probabilities with the constraint that the impactor must at least have an unspecified carbonaceous chondrite composition:

\[
P(\text{comet} | CC) = P(\text{CC} | \text{comet}) \times P(\text{comet}) + P(\text{CC} | \text{asteroid}) \times P(\text{asteroid})
\]

where $P(\text{CC} | \text{asteroid}) = 50%$ is the probability of a carbonaceous chondrite composition given an asteroid impactor, and $P(\text{CC} | \text{comet}) = 100%$. The probability of a comet impactor based on just the impact rates and then based on the impact rates and the need to be a carbonaceous chondrite are plotted in figure 2 as a function of $N$, the number of cometary fragments per break-up. The requirement that the impactor match a carbonaceous chondrite somewhat increases the likelihood the impactor was a comet (from 12% to 21% if $q = 2$, $N = 20$), but in general a comet still would be unlikely unless $N > 600$.

Of course, if the geochemical criterion is that the impactor must match a CM or CR chondrite composition and/or must match the Ir anomaly, then the probability of an asteroid matching that exact composition is somewhat reduced but is still plausible, whereas a comet can be ruled out. The relative probability of a comet is 0%.

In summary, despite the claims made by Siraj & Loeb, the case for an asteroid impactor is very strong. The enhancement in impact rates of comets due to tidal disruption is sensitive to the number of fragments generated per disruption, $N$, but they did not acknowledge this uncertainty or parameterize this input. Comet fragments are more likely impactors than asteroids only if the number of generated fragments is $N > 600$, the value arbitrarily and without good justification chosen by Siraj & Loeb, but far exceeding the values $N = 10–30$ suggested by observations of Shoemaker–Levy 9 and crater chains.
Siraj & Loeb claimed the likelihood of a comet is increased after imposing the constraint that the impactor had carbonaceous chondrite composition; but they applied a double standard by requiring the asteroid impactor to be a CM chondrite, but not demanding comets be a particular type of carbonaceous chondrite. In fact, the impactor must be a CM or CR chondrite, and this makes asteroids plausible but rules out comets, which are only strongly associated with CI chondrites. Of course, the observed amount of Ir in the K–Pg boundary clay layer argues in favour of an asteroid but rules out a comet, but this key evidence was ignored entirely by Siraj & Loeb.

The challenges of interdisciplinary science
The nature of the Chicxulub impactor is an outstanding problem at the intersection of Earth science and astronomical sciences. Problems like these are of great general interest. As they allow researchers in one field to leverage the results of another, these sorts of investigations should be encouraged. But the fact that the work by Siraj & Loeb has so many flaws easily rectified by a quick review of the literature highlights many of the challenges to engaging in interdisciplinary science.

One challenge is that despite the greater need to synthesize the literature, there are fewer venues for doing so. While the constraints about which carbonaceous chondrite types match the impactor are all available, these are dispersed among a variety of journals (Earth and Planetary Science Letters, Geochemia et Cosmochimica Acta, Meteoritics and Planetary Science, Nature, etc.). It is difficult for an astrophysicist to become fluent in researching this entirely new field of literature, which samples more journals than in astrophysics.

Another challenge is the need to go beyond just accessing information from another field, to understanding the context and significance of that information. In the internet era, it is easier than ever to learn of findings from another field. It is not so easy, but still possible, to learn the jargon of that field and know how the data were acquired. More difficult still, though, is appreciating the context of the information: what are that field’s underlying, unspoken assumptions, and what information is missing? Often there are differences in scientific culture between fields about how they deal with uncertainty, or what constitutes a burden of proof. It is possible and rewarding to engage in interdisciplinary research, but it starts with opening dialogues with researchers in other fields, based on mutual respect and a lot of listening.

Interdisciplinary research also poses challenges to the peer review process itself. It is difficult but necessary to find the needed range of reviewers for papers like the one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics and one by Siraj & Loeb, bridging celestial mechanics and cratering statistics. Finding and accommodating跨度 all the disciplines pertinent to the paper, though this is easier said than done. Finding and accommodating multiple reviewers takes longer and is at cross purposes with making manuscripts "swiftly visible". Being deliberative and making a paper’s conclusions precise is at cross purposes with making manuscripts “highly discoverable”.

But these practices must be applied to interdisciplinary papers to ensure they meet the scientific standards of all the fields involved, so that disciplines can build off each other’s results.

**“It is difficult for an astrophysicist to become fluent in researching this new field of literature”**

significant confinement of CM chondrites with all carbonaceous chondrites. But a reviewer with a background in astrophysics and the culture of how models deal with uncertainty would be most likely to demand that the number of fragments be considered a free parameter, and the sensitivity of the results to that parameter explored. Each of these mistakes severely undercuts the authors’ arguments, but only a rare single reviewer would have caught all of them.

Other issues are less substantive but equally telling that the paper was not reviewed by referees from different disciplines. Perhaps it wouldn’t take an astrophysicist to catch the logical inconsistency that something happening once per 350Myr was dismissed as too rare to happen once in 250Myr. But only someone familiar with asteroids would have noticed the name Baptista was misspelled repeatedly. A geologist would have complained that the defunct term “K–T” was used instead of “K–Pg”, K–Pg has been standard since 2009, and K–T is discouraged by the International Commission on Stratigraphy. Likewise, a palaeontologist would have objected to the title of the paper, which purports to explore the cause of the “dinosaur extinction". While it is commonly accepted that the Chicxulub impact is associated with and likely precipitated the Late-Cretaceous mass extinction event that killed ~75% of all plant and animal species on land and in the oceans, not just dinosaurs (and, more precisely, just the non-avian dinosaurs), this remains an area of ongoing scholarship (e.g. Schulte et al. 2010, Chiarenza et al. 2020), and at no point did the paper explore the “dinosaur extinction”. The authors chose a title flashier than the more accurate “origin of the Chicxulub impactor”; but it is not scientifically rigorous, and a geologist or palaeontologist reviewer would have objected.

The solution to the problem of how to review interdisciplinary papers is for journal editors to find reviewers spanning all the disciplines pertinent to the paper, though this is easier said than done. Finding and accommodating multiple reviewers takes longer and is at cross purposes with making manuscripts “swiftly visible”. Being deliberative and making a paper’s conclusions precise is at cross purposes with making manuscripts “highly discoverable”. But these practices must be applied to interdisciplinary papers to ensure they meet the scientific standards of all the fields involved, so that disciplines can build off each other’s results.

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