Recent multi-kiloton impact events: are they truly random?

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ABSTRACT
It is customarily assumed that Earth-striking meteoroids are completely random, and that all the impacts must be interpreted as uncorrelated events distributed according to Poisson statistics. If this is correct, their impact dates must be uniformly spread throughout the year and their impact coordinates must be evenly scattered on the surface of our planet. Here, we use a time- and yield-limited sample of Earth-impacting superbolides detected since 2000 to explore statistically this critical though frequently overlooked topic. We show that the cadence of these multi-kiloton impact events is incompatible with a random fall pattern at the 0.05 significance level or better. This result is statistically robust and consistent with the observed distribution of the longitudes of the ascending nodes of near-Earth objects (NEOs). This lack of randomness is induced by planetary perturbations, in particular Jupiter’s, and suggests that some of the recent, most powerful Earth impacts may be associated with resonant groups of NEOs and/or very young meteoroid streams. An intriguing consequence of this scenario is that the impact hazard of Chelyabinsk-like objects should peak at certain times in the year.

Key words: celestial mechanics – meteorites, meteors, meteoroids – minor planets, asteroids: general – planets and satellites: individual: Earth.

1 INTRODUCTION
Small bodies dominate the risk of sudden Earth impacts with just local, not global effects (Brown et al. 2013). Earth-striking meteoroids are believed to be random in nature. In order to experience an impact, the nodal distance between the orbits of the Earth and the parent body of the meteor must be smaller than the cross section of our planet for that particular body, and both have to pass at the same time by the mutual node. If the nodes of the orbits of the impactors have a random and uniform distribution, any associated impact events should be truly random. The paths followed by these objects are strongly perturbed, and exhibit fast and chaotic nodal precession over time-scales of $\sim 10$ Myr (see e.g. Ito & Malhotra 2006). It is therefore not surprising that most studies assume that the angular elements, in particular the longitude of the ascending node, of the orbits of near-Earth objects (NEOs) are randomly and uniformly distributed in the range $0-2\pi$. For many, this intrinsic chaoticity necessarily means that they are completely random, and that all the impacts must be interpreted as uncorrelated events distributed according to Poisson statistics. But the angular elements of the orbits of NEOs do not strictly follow uniform random distributions and this is the result of planetary perturbations, mainly those of Jupiter (JeongAhn & Malhotra 2014).

Even if the amount of data on powerful airburst events is still scarce and incomplete (Brown et al. 2013), the theoretical notion that some of them may not be random is particularly relevant in the context of Planetary Defense initiatives and deserves to be explored. However, and because of the small size of the current data set, the results of any such study shall be necessarily limited in scope as only very large effects are likely to be reliably identified. Here, we use a time- and yield-limited sample of Earth-impacting superbolides detected by Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) infrasound sensors, and others from the literature, since 2000 to perform a rigorous statistical assessment of the existence of time-correlated impacts. The superbolide detections were reported by the B612 Foundation using CTBTO data. This Letter is organized as follows. The sample used in this study is presented and discussed in Section 2. Its presupposed randomness in time is put to the test in Section 3. Section 4 investigates the putative randomness in impact coordinates. Possible sources of non-randomness are introduced in Section 5. Our results are discussed in Section 6 and conclusions are summarized in Section 7.

2 THE B612 SAMPLE AND MORE
Since 2000, the CTBTO infrasound sensors of the International Monitoring System (IMS) network have detected 26 events with an individual explosive energy in excess of 1 (and up to $\sim 500$) kt of Trinitrotoluene (TNT) equivalent. These superbolide detections were reported by the B612 Foundation using CTBTO data; they are

1 https://b612foundation.org/list-of-impacts-from-impact-video/
2 http://newsroom.ctbto.org/2014/04/24/ctbto-detected-26-major-asteroid-impacts-in-earths-atmosphere-since-2000/
not the only detections compiled during that period of time. Some of them are among the most energetic events ever instrumentally recorded; their yields are comparable to those of typical nuclear weapons currently stocked. Higher yield, or amount of energy released, implies higher potential number of casualties and increased net damage efficiency. In absence of clandestine nuclear tests, these events have been interpreted as resulting from Earth-impacting fireballs or superbolides disintegrating as they travel through the atmosphere. The most extraordinary event recorded so far by the IMS network is the Chelyabinsk superbolide, on 2013 February 15 (Brown et al. 2013; Le Pichon et al. 2013). The list of events appears in Table A1 and their geographical and calendar day distributions are displayed in Fig. 1. It includes seven additional events from the published literature. They correspond to a time- and yield-limited sample of Earth-impacting superbolides.

The list of events in Table A1 is controversial. It was released by the B612 Foundation on 2014 April 22 during a press conference and it is based on research presented in Brown (2014). The original release included some errors. An 18 kt event observed in Botswana on 2009 November 24 and six others with yields in the range 1.7–5 kt were omitted. There was no Tasman Sea event on 2010 December 25, the latitude of the actual 33 kt event was 38° N not S (see footnote 3). The event listed as Indian Ocean on 2007 September 22 actually took place in the South Pacific Ocean. The event observed from Finland on 2007 July 6 was not included in the video release. Our final list includes 33 events; as a time- and yield-limited sample, it is probably quite complete. The size of this sample already suggests that the frequency of this type of impacts is from 3 to 10 times greater than previously believed (see original estimates in Brown et al. 2002). Any significant deviations from near-completeness imply a further enhanced risk of locally dangerous impacts; for example, if the sample is just 50 per cent complete, we should expect an average close to five such impacts per year instead of nearly two (see Fig. 1 bottom panel).

Only in one case, the Almahatta Sitta event of 2008 in Sudan (Jenniskens et al. 2009), the incoming body was detected in advance but only hours before impact. The first obvious conclusion to be drawn from these data is that asteroid impacts, at least those of objects of a size under ∼20 m, are not extraordinarily rare. In addition, the fraction of our planet covered by oceans is 65.7 per cent and the actual number of impacts away from land masses is 60.6 per cent; overall, 17 impacts are located in the Northern hemisphere. This suggests a uniform geographical distribution of impacts, perhaps compatible with a random origin. However, if Earth-impacting meteors are sporadic, random events, they are expected to be uniformly distributed in calendar day across the year. Thirteen impacts have been recorded on the first part of the year and 20 on the second, a 21 per cent relative difference with respect to the evenly-distributed scenario. This suggests a non-uniform temporal pattern of impacts. These apparent trends could be just coincidences but, statistically speaking, what are the odds of observing patterns like the ones found in calendar day and geographical distribution?

3 EARTH IMPACTS: A PROBABILISTIC APPROACH

The answer to the time-related section of the question asked above is connected with the famous “Birthday problem” of Probability Theory (von Mises 1939; Abramson & Moser 1970; Diaconis & Mosteller 1989), the DNS cache poisoning technique used in Internet attack or DNA matching in Forensic Science (Weir 2007): the probability of collision among a set of n uniformly random numbers. In this context and if the nodes of the orbits of NEOs are not uniformly distributed (see figs 4 and 5 in JeongAhn & Malhotra 2014), a measurable deviation from a uniform distribution in calendar day should be present in the available data.

Let us consider a sample of n Earth-impact events producing superbolides. We want to compute the probability of having two or more events on the same calendar day, but probably in different years, under the assumption that they are not time correlated. All calendar days have an equal chance of having an impact. We will count calendar days taking into account the existence of common and leap years but, for the actual calculations, we will use years of 365 d. In our analysis, we will also study almost coincidences, when two or more events are separated by one, two or three days. There are well-known formulae (e.g. Diaconis & Mosteller 1989) for same calendar-day events but, for practical reasons, the probabilities discussed here have been evaluated using Monte Carlo techniques as these are more flexible. In Table A1 there are four same-day pairs (including a set of three events on the same calendar day,
For such sample and in the purely non-correlated case, the most probable number of pairs with the same calendar day is 1 (35.7 per cent). In Table A1 there are nine pairs of events within one or less calendar-days difference. The likelihood of finding nine such pairs in a non-correlated sample is 0.0190. There are also 14 pairs of events within two or less calendar-days difference. The probability of finding such number of pairs in a non-correlated sample is 0.0093. Finally, there are 16 pairs of events within three or less calendar-days difference but the likelihood of finding this many pairs in a non-correlated sample is 0.0216. The number of same (or nearly same-day) coincidences is simply too high to be the result of chance alone. It is statistically obvious that the impact events in Table A1 are not uniformly distributed in time. They are far from sporadic in strict sense.

The evaluation of the various probabilities presented here was carried out using the Monte Carlo method (Metropolis & Ulam 1949). A typical experiment consists of $10^{10}$ tests of uniformly distributed (in the interval $1\text{–}365$) integer samples of 33 numbers. For each sample, the number of same (or near same) calendar-day coincidences (or collisions) are counted and this value is divided by the number of trials. Multiple experiments were performed to check for consistency and, when applicable, the probability values were systematically checked against analytical results previously published (Abramson & Moser 1970; Diaconis & Mosteller 1989).

4 GEOGRAPHICAL DISTRIBUTION

The answer to the geography-related section of the question is linked to the mathematical problem of "Sphere Point Picking". In this section, the random points on the surface of a sphere have been generated using an algorithm due to Marsaglia (1972). The continuous curve in Fig. 2 (top panel) is based on experiments consisting of $10^6$ tests. In any case, currently accepted models predict a non-uniform geographical distribution of impacts (Le Feuvre & Wieczorek 2008); as the source of the impactors (the NEO population) is not isotropic, latitudinal variations are expected (see figs 6 and 7 in Le Feuvre & Wieczorek 2008).

Figure 2 (top panel) shows the expected distribution of separations between events on the surface of a sphere, black discontinuous line, if they are uniformly distributed. The most probable separation is $\pi r/2$, where $r$ is the radius of the sphere. The distribution associated with the data in Table A1 is far from regular but we cannot conclude that the points are not coming from a uniform distribution. Here, we adopt Poisson statistics and use the approximation given by Gehrels (1986) when $n_p < 21$: $\sigma = 1 + \sqrt{0.75 + n_p}$, where $n_p$ is the number of pairs. Only one bin shows a deviation $> 2\sigma$ (2.2$\sigma$). The distribution is similar for pairs of events within three or less calendar-days difference. The number of impacts with latitude $\in (-40, 40)^\circ$ is 25 and outside that range we found 8 (see Fig. 2 bottom panel); a uniform sample should have 21.2 and 11.8 events, respectively. In principle, this is consistent with predictions in Le Feuvre & Wieczorek (2008). In longitude, the distribution appears to be uniform (see Fig. 2 middle panel) but there is a relatively large number of events at longitudes in the range (15, 40)$^\circ$E, 7. A uniform distribution predicts two events in that region, the deviation is close to $2\sigma$.

5 YOUNG STREAMS VERSUS RESONANT GROUPS

The Chelyabinsk event of 2013 February 15 and the South China Sea event of 2000 February 18 are separated by three calendar days and their impact nodes are close to 146.5$^\circ$. Both impacts may have a common source. The pre-impact orbit of the parent body of the

http://mathworld.wolfram.com/SpherePointPicking.html
Chelyabinsk impactor is well understood (see e.g. de la Fuente Marcos \& de la Fuente Marcos 2014) and it may be associated with a resonant family of asteroids. The North Pacific Ocean event of 2001 April 23, between Hawaii and California, and the Sutter’s Mill meteor of 2012 April 22 were observed on the same calendar day. The Santiago del Estero event in Argentina was observed on 2013 April 21. The impacting node was \(\sim212^\circ\). For the Sutter’s Mill meteor, it happened at the descending node; the parent body being an object moving in an orbit close to those of the Jupiter-family comets (Jenniskens et al. 2012). The two same-day impacts are very likely related; the Argentinian event appears to be unrelated, its properties being too different (see footnote 3). The Chelyabinsk event of 2013 February 15, was traced to the Nysa-Polana asteroid family (Gayon-Markt et al. 2012). The Almahatta Sitta event was caused by the impact of the Apollo asteroid 2008 TC\(_{32}\) (Jenniskens et al. 2009). The origin of asteroid 2008 TC\(_{32}\) was traced to the Nysa-Polana asteroid family (Gayon-Markt et al. 2012). On 2002 November 10, there was an impact event on the North Pacific Ocean and on 2005 November 9 another impact was observed in New South Wales, Australia. The impact node was nearly \(47^\circ\). The South Pacific Ocean event of 2007 December 26 and the North Pacific Ocean event of 2010 December 25 have an impact node \(\sim93^\circ\).

More than 50 per cent (20/33) of the events in Table A1 show some degree of time correlation and the analysis of the geographical distribution also suggests that a certain degree of spatial correlation at the \(\sim3\sigma\) level could be present, see Fig 2. For decades, it has been assumed that Earth-impact events were uncorrelated. Unlike prior efforts, our statistical analysis shows that the customary assumption that Earth-impact events are sporadic and of random origin is incorrect, at least in the case of the most powerful and recent ones. The most natural and simple explanation is to admit the existence of very young meteoroid streams, resulting from the breakup of an asteroid or comet, and/or resonant streams in which secular resonances force a group of objects to orbit around the Sun following similar orbits; impacts occur when their paths intersect that of our planet. A resonant stream may well be the source of the parent body of the Chelyabinsk superbolide and related bodies (de la Fuente Marcos \& de la Fuente Marcos 2013, 2014). Very young meteoroid streams may be disrupted in just 30 years or less (Lai et al. 2014); resonant streams are somewhat permanent when compared with their ephemeral relatives resulting from breakups because they are continually being replenished via resonance capture. Hybrid streams may exist (see e.g. Williams \& Ryabova 2011). The material trapped in a resonant stream may be diverse in composition producing meteorites of various types but debris from a breakup is expected to be homogeneous in composition.

6 DISCUSSION

Although our analysis provides robust statistical proof that the cascade of recent multi-kiloton impact events is incompatible with a random fall pattern at the 0.05 significance level or better, it may be argued that the data in Table A1 are not an accurate temporal and spatial representation of all superbolides striking Earth with yields \(>1\) kt within the time frame 2000-2013. It is true that for the events included here the uncertainties in impact time (\(\sim10\) s) and coordinates (\(\sim1^\circ\)) are too small to affect significantly any of our conclusions, but yields are model dependent and a difference of a factor of 3 between models is not unusual (Brown et al. 2013). However, this is only relevant for yields \(<3\) kt. On the other hand, a number of events with explosive energy under 1 kt, but within the factor 3 region, have been left outside our analysis; their number may compensate for any wrongfully included, underperforming event. As pointed out above, we believe that the sample used here is reasonably complete, especially for the most powerful events. An average annual number of multi-kiloton impacts much higher than three does not appear to be supported by currently available observations. It is true that the geographical detection efficiency during the first half of the period studied here, when the IMS network was far from complete, was lower (Le Pichon, Ceranna \& Vergoz 2012). The IMS network was 75 per cent complete by the end of 2013; now it is almost 80 per cent complete. Seasonal variations in the stratospheric winds are also critical, IMS detection capabilities are best around January and July, and worst near the equinox periods (Le Pichon et al. 2012). In their study, Le Pichon et al. (2012) consider ground sources and not superbolide outbursts above the tropopause; their results are based on the full IMS infrasound network, not the currently installed network. From Table A1 we have that 20 events were observed from 2000 to 2006 and 13 events from 2007 to 2013. Also, only one event was observed in January, July and March; September has the record with six detections. In summary, no statistically significant biases of systematic nature appear to be present in our sample. The year-to-year variation in the number of impacts can be naturally explained within the context of secular resonances (see the clustered, periodic close-approaches characteristic of resonant groups in fig. 4 in de la Fuente Marcos \& de la Fuente Marcos 2014). The only true bias affects bodies moving in very Earth-like orbits; if the orbit of a meteoroid is only slightly different than that of the Earth, the encounter speed in a collision may be very low and slower meteors produce less ionization. Such impactors are much less likely to be observed (using either radar, infrasound or optical equipment) than higher encounter speed meteors moving in very eccentric orbits, unless they are relatively large. No objects of this type appear to be included in Table A1.

Regarding Earth strikes, a coherent debris stream, resonant or not, is characterized by its radiant. If an impactor is associated with a certain stream, its radiant must be above the local horizon at the time of the event. Although a putative radiant above the horizon at the time of impact does not secure a linkage, the opposite is true: if
the radiant is below the horizon, we can strictly rule out any connection. This criterion has been used to discard the 2013 April 21 or the 2009 October 8 events in the previous section. It is widely accepted that orbital destruction is far too efficient to allow the existence of long-lived near-Earth meteoroid streams. Near-Earth meteoroid streams are made of debris of asteroidal or cometary origin (Jopek & Williams 2013). Groups of objects moving initially in similar trajectories lose all orbital coherence in a short time-scale (Pauls & Gladman 2005; Rubin & Matson 2008; Lai et al. 2014). However, small bodies part of debris streams formed during the last few decades may still follow very similar orbits, including having a common node. Such concentration of nodes has not been observed for large NEOs. Schunová et al. (2012) could not find any significant near-Earth meteoroid streams among currently known objects but they could not refute their existence. However, Schunová et al. (2014) confirmed that streams from tidally disrupted objects can only be detected for a few thousand years after the disruption event and only if the parent body is large enough. The debris field made of $10^2$–10 m fragments of a disrupted progenitor smaller than about 350 m in diameter cannot be detected by current techniques. Such a very young meteoroid stream could easily be the source of some of the events discussed here. An example of an already-evolved meteoroid stream is the one responsible for the Geminids meteor shower. The parent body of this stream is the asteroid (3200) Phaethon (e.g. de León et al. 2010) but other smaller bodies like (155140) 2005 UD (Kinoshita et al. 2007) or (225416) 1999 YC (Kasuga & Jewitt 2008) are very probably associated fragments. Phaethon is still actively producing meteoroids (Jewitt & Li 2010; Ryabova 2012; Li & Jewitt 2013) that may eventually end up as meteorites (Madiedo et al. 2013).

7 CONCLUSIONS

The pattern of recent multi-kiloton impact events is not random. This conclusion cannot be attributed to observational biases and may have its origin in secular planetary perturbations. Our main results are summarized as follows:

- The cadence of recent multi-kiloton impact events is incompatible with a random fall pattern at the 0.05 significance level or better.
- Statistically, the impact coordinates of these events do not follow a uniform distribution at the $\sim 2\sigma$ level.
- Non-random Earth impacts may have their source in very young and/or resonant streams, eight candidates are proposed.

Resonant and/or very young meteoroid streams may dominate the flux of impactors having just local effects. The intrinsic chaoticity characteristic of these streams makes long-term predictions relatively useless in this case and forces any realistic Planetary Defense programme to keep an eye permanently on this population; quite literally, the meteoroid streams responsible for local impacts today may not be the same a few decades from now. Although most of the impact events in Table[A1] ended up with the disintegration of the incoming body high up in the atmosphere, sometimes above remote parts of the ocean, causing virtually no problems on the ground (Chelyabinsk event excluded, Popova et al. 2013), early identification of time- and, perhaps, space-correlated events may help mitigating subsequent impacts associated with the same streams.

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Sudden Earth impacts: are they truly random?
APPENDIX A: THE TIME- AND YIELD-LIMITED SAMPLE OF EARTH-IMPACTING SUPERBOLIDES

As pointed out above, the time- and yield-limited sample of Earth-impacting superbolides used in this research is based on the controversial B612 sample (26 events) and includes seven additional events from the literature. The list of events appears in Table A1.

APPENDIX B: NOTE ADDED IN PROOF

After this work was accepted by MNRAS Letters, J. M. Madiedo pointed out that the following paper had arrived at similar conclusions:

Sánchez de Miguel A., Ocaña F., Zamora S., Tapia C., Santamaria A., de Burgos A., 2014, in Garzón Guerrero J. A., López Sánchez A. R., eds, Libro de Actas del XXI Congreso Estatal de Astronomía. Granada, Spain

However, we remark that the sample used in the study of Sánchez de Miguel et al. (2014) presents multiple biases: notably, it is sparse in time and locally restricted, to the USA and Spain. Furthermore, its primary sources (newspapers) are not necessarily reliable.