

EARTH IN THE COSMIC SHOOTING GALLERY

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The terrestrial impact rate appears to be substantially higher than current near-Earth object population models imply, consistent with a significant unseen cometary contribution to the terrestrial impact hazard.

Introduction

As a result of a growing number of asteroid and comet discoveries in recent years by dedicated ‘Spaceguard’ survey programmes aimed at finding Near-Earth Objects (NEOs) on potentially Earth-colliding trajectories, and as a result too of improved dynamical modelling of the NEO population, the impact rate by NEOs of various sizes is thought to be fairly well constrained. The problem can be approached in at least three ways. One is simply to model the whole population of potential impactors, based on objects discovered during large-scale surveys^{1,2}. A second is to consider the cratered surfaces of the Earth and Moon, and estimate the flux of different-sized projectiles by counting craters^{3,4}. A third is to focus attention on objects that happen to pass very close to Earth. Although there are relatively few such objects, this method has the advantage of constraining the flux of relatively small and/or faint objects. Moreover, objects that actually collide with Earth, or pass (or are predicted to pass) very close, represent observational ‘ground truth’ so far as impact statistics are concerned.

It is important also to note that occasional exceptional objects with a small (albeit nonzero) probability of hitting the Earth on centennial timescales continue to make the news and are frequently placed on so-called ‘risk’ web-sites by virtue of their rather close approaches. By applying the third of the methods outlined above, we ask whether observations of such ‘close-approach’ NEOs, with sizes ranging from large meteorites (i.e. several metres) up to comets (i.e. tens of kilometres or more), are consistent with NEO impact rates determined by either of the other two methods. In particular, we highlight four independent sets of data which taken together suggest a substantially higher impact rate than is implied by the current, generally accepted NEO population models. We conclude that there is a significant unseen and unmodelled component of the terrestrial impact hazard, some of which may be attributed to low-activity or dormant comets.

Statistics of close-approach objects

Consider a heuristic model in which a population of objects has essentially random velocities with respect to the Earth and the number of close approaches per unit time within some impact parameter b is proportional to b^2 . Thus, if the mean interval between terrestrial impacts (i.e. $b < R_{\oplus}$, where $R_{\oplus} = 6,400$ km is the radius of the Earth, neglecting a relatively small correction for gravitational focusing) for such a population is t_{\oplus} , then within any observed time interval t_{obs} we would expect on average to see one encounter with an impact parameter less than b_0 , where

$$b_0 = (t_{\oplus}/t_{\text{obs}})^{1/2} R_{\oplus} \quad (1)$$

A priori, the number of passages within a distance b during the time interval t_{obs} is determined by a Poisson distribution with mean $(b/b_0)^2$. The probability of at least one approach within this distance is

$$p_{\text{obs}} = 1 - \exp(-b^2/b_0^2) \quad (2)$$

When $b/b_0 \ll 1$, $p_{\text{obs}} \simeq (b/b_0)^2$. It is interesting to note that the frequency distribution of *minimum* impact parameters b_{min} during such a time interval is given by

$$f(b_{\text{min}}) = \frac{2b_{\text{min}}}{b_0^2} \exp(-b_{\text{min}}^2/b_0^2) \quad (3)$$

We note that the real world of close-approach impact statistics is more complicated than this⁵, but the model nevertheless provides a realistic basis for the following discussion.

An exceptional close-approach asteroid

On 13th April 2029 a small asteroid in an Earth-like orbit, 2004 MN₄ will pass within 5–6 Earth radii of the Earth⁶, becoming a naked-eye object crossing the sky at tens of degrees per hour. 2004 MN₄ was recently named (99942) Apophis, after the Egyptian god of evil and destruction, Apep, and its likely diameter in excess of 300 metres corresponds to a potential impact energy of 1,000 megatons or more. Recent NEO population models¹ predict impacts by such bodies at 63,000 year intervals, with a probable uncertainty of about 50%.

Here, we have $t_{\oplus} = 63,000$ yr, $t_{\text{obs}} = 20$ yr (or perhaps 200 yr, if the whole time since asteroids have been known is considered as the observed interval), and $b_{\text{obs}} = 5\text{--}6 R_{\oplus}$. The *a priori* probability of observing an object such as 2004 MN₄ is then of order 0.01 or 0.1 (the range depending on the choice of t_{obs}). The close approach of 2004 MN₄ in 2029 is more consistent with a mean impact interval on the Earth for such objects on the order of 500–5,000 years rather than 63,000 years. It is noteworthy that a similar result was obtained by Hughes⁴ by considering the near-miss distances of known NEOs passing the Earth in 2002. He gave the result (*loc. cit.* eqn. 10) $\dot{N}_{\text{E}} \simeq 3.4 \times 10^{-4} (d/300 \text{ m})^{-3} \text{ yr}^{-1}$, indicating a mean impact interval for such objects on the order of 3,000 years. Thus, our result is robust. Since the discovery of objects of this size is likely to be very incomplete, close approaches similar to that of 2004 MN₄ would seem to be much more common than expected from current NEO population models.

The ‘Tunguska’ impact rate

The ~10 megaton 1908 Tunguska impact turns out to be similarly rare. Current NEO models suggest such impacts occur on Earth every $t_{\oplus} = 2000\text{--}3000$ years², whereas this Siberian impact ($b_{\text{obs}} < 1 R_{\oplus}$) occurred within the last 100 years. Following the same reasoning, the *a priori* probability of a ‘Tunguska’ event within the last $t_{\text{obs}} \simeq 100$ yr is about 0.05 or less.

An independent estimate of the frequency at which bodies of this size currently pass within near-Earth space comes from lunar meteorites. In fact, hydrocode simulations suggest that the minimum size of impactor needed to eject sufficient material from the Moon to produce fragments that might be observed on Earth as lunar meteorites is approximately Tunguska size or larger^{7,8}. A large majority of the currently known 30 or so lunar meteorites attributed to independent falls originate from different lunar impacts, and most of the dated meteorites have been ejected from the Moon within the last 100,000 years⁹. Thus, we conclude that there are

probably at least 15 independent lunar meteorite source craters with ages less than 100,000 years, and so at least 15 Tunguska-sized impactors on the Moon within this time-scale.

However, this is a lower limit to the ‘Tunguska’ impact rate on the Moon. Suppose that, in fact, there have been N such impactors within the last 100,000 years. Then if N was close to 15 it would be extremely unlikely that the present sample of lunar meteorites would represent the whole range of lunar impact events; in effect, one would expect to see multiple source pairs amongst the observed independent lunar meteorite falls. Combinatorial calculations can be used to quantify this argument, and yield a 95% confidence interval $N \geq 26$ for producing exactly one or no source pairs among a sample of 15 independent meteorites. (The corresponding figure for no source pairs is $N \geq 41$.)

Moreover, these calculations assume that each event yields equal numbers of detectable meteorites, whereas in reality — when the highest energy events yield more (cf. ref. 10) — an absence or near absence of pairs is even less likely for a given number of sources. Thus, even more sources would be needed to explain the observed scarcity of source pairs. These estimates therefore suggest that the true number of lunar meteorite producing impacts during the past 100,000 years is rather higher than the lower limit of 15, and in what follows we conservatively assume a figure of 25 such impacts on the Moon.

A rough estimate of the rate of such meteorite producing impacts on the Moon is therefore one per 4,000 years. The implied ‘Tunguska’ impact rate on Earth (taking account of the ratio of 13.5 in surface area between the two bodies, and neglecting gravitational focusing) is therefore one event every 300 years and probably rather more frequent. This conservative estimate of the mean interval between Tunguska-size impacts on the Earth is much shorter than the current preferred value of 2,000–3,000 yr, and again any incompleteness in the discovery of lunar meteorites (including destruction by terrestrial erosion) acts in the direction of increasing the estimated rate.

The cometary impact rate

On a longer time-scale, an object (comet or asteroid) with a diameter of 10 km, similar to the diameter of the active comet C/1983 H1 IRAS-Araki-Alcock¹¹, is estimated to collide with the Earth every 150 million years¹², and active comets larger than 7 km once every 3 billion years¹³. Here, we have $t_{\oplus} = 3 \times 10^9$ yr and $t_{\text{obs}} = 20$ yr (or 200 yr, if the period during which comets have been scientifically observed is considered). In either case, with $b_{\text{obs}} = 0.0312$ AU = $732 R_{\oplus}$, we infer a very low *a priori* probability of an active comet as large as Comet IRAS-Araki-Alcock coming so close to the Earth. This comet had unusually low activity, suggesting that current NEO population models are again underestimating the terrestrial impact rate by such bodies.

Conclusion

Taking these arguments together, an appeal to small number statistics seems unconvincing. It instead suggests that the terrestrial impact rate is substantially higher than current NEO population models imply. This is consistent with an unseen cometary contribution to the terrestrial impact hazard^{14,15}, questioning the conclusions, in this respect, of the 2003 NASA NEO Science Definition Report¹³.

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References

- (1) A. Morbidelli, R. Jedicke, W.F. Bottke, P. Michel and E.F. Tedesco, “From magnitudes to diameters: the albedo distribution of near Earth objects and the Earth collision hazard”. *Icarus*, **158**, 329–342, 2002.
- (2) J.S. Stuart and R.P. Binzel, “Bias-corrected population, size distribution, and impact hazard for the near-Earth objects”, *Icarus*, **170**, 295–311, 2004.
- (3) D.W. Hughes, “A new approach to the calculation of the cratering rate of the Earth over the last 125 ± 20 Myr”, *MNRAS*, **317**, 429–437, 2000.
- (4) D.W. Hughes, “The approximate ratios between the diameters of terrestrial impact craters and the causative incident asteroids”, *MNRAS*, **338**, 999–1003, 2003.
- (5) S.P. Manley, F. Migliorini and M.E. Bailey, “An algorithm for determining collision probabilities between small solar system bodies”, *A&A, Suppl. Ser.*, **133**, 437–444, 1998.
- (6) D. Chandler, “Too close for comfort”, *New Scientist*, **186**, No. 2505 (25 June), 34–38, 2005. See also <http://neo.jpl.nasa.gov/news/news149.html>; <http://newton.dm.unipi.it/cgi-bin/neodys/neoibo>.
- (7) J.N. Head, “Lunar meteorite source crater size: constraints from impact simulations”. *Lunar & Planet. Sci.*, **XXXII**, Paper No. 1768, 2001.
- (8) J.N. Head, “The relative abundance of recently-launched meteorites from the Moon and Mars”. *Lunar & Planet. Sci.*, **XXXIV**, Paper No. 1961, 2003.
- (9) R.L. Korotev, B.L. Jolliff, R.A. Zeigler, J.J. Gillis and L.A. Haskin, “Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust”. *Geochimica et Cosmochimica Acta*, **67**, 4895–4923, 2003.
- (10) D. Steel, “Distributions and moments of asteroid and comet impact speeds upon the Earth and Mars”, *Planet. Space Sci.*, **46**, 473–478, 1998.
- (11) J.K. Harmon, D.B. Campbell, A.A. Hine, I.I. Shapiro and B.G. Marsden, “Radar observations of comet IRAS-Araki-Alcock 1983d”. *ApJ*, **338**, 1071–1093, 1989.
- (12) B.M. French, “Traces of Catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures.” LPI Contribution No. 954, Lunar and Planetary Institute, Houston, 1998.
- (13) G.H. Stokes, D.K. Yeomans, W.F. Bottke, D. Jewitt, S.R. Chesley, T.S. Kelso, J.B. Evans, R.S. McMillan, R.E. Gold, T.B. Spahr, A.W. Harris and S.P. Worden, “Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters”. *Report of the Near-Earth Object Science Definition Team*, NASA, Office of Space Science, Solar System Exploration Division, Maryland, USA, 2003. See also <http://neo.jpl.nasa.gov/neo/neoreport030825.pdf>.
- (14) W.M. Napier, J.T. Wickramasinghe and N.C. Wickramasinghe, “Extreme albedo comets and the impact hazard”. *MNRAS*, **355**, 191–195, 2004.
- (15) V.V. Emel’yanenko and M.E. Bailey, “Capture of Halley-type comets from the near-parabolic flux”. *MNRAS*, **298**, 212–222, 1998.