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Invited Review

The case for significant numbers of extraterrestrial impacts through the late Holocene

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ABSTRACT: When astronomers tell us that there should have been numerous impacts from space during the last five millennia, when impact craters exist on land and more impacts can be assumed over the oceans, why are historians, archaeologists and palaeoecologists not diligently seeking evidence for these impacts, and their effects? This article reviews just some of the relevant evidence for impacts. In turn this suggests that ablation material, background material from space, and micro-tektites, should all be present in ocean cores, ice cores, peat, and lake sediments. It seems that almost no efforts have been made to find evidence that might link to the known crater fields, or to identify and date periods of enhanced cosmic activity. The question must be, why?

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KEYWORDS: extraterrestrial impacts; comets; craters; tree rings; ice cores.

Background

When the 20 or so fragments of comet Shoemaker–Levy 9 ploughed into the giant planet Jupiter in July 1994 it finally rang an alarm bell for scientists and astronomers (Lewis, 1996). Up to the time of the impacts arguments were being batted back and forth regarding the composition of the comet fragments and their likely effects. Opinions varied between wide extremes: there were those who thought the relatively tiny comet fragments (up to 1 km in diameter) would simply be swallowed up by the atmosphere of the giant planet (diameter ca.143 000 km), while others estimated that the resulting explosions in the dense Jovian atmosphere would be in the 10^8–10^6 Mt class.

For those who have not thought about such things, we know that the Tunguska object that exploded in the Earth's atmosphere on 30 June 1908 produced a blast roughly equivalent to 15 megatons of TNT (Clube and Napier, 1990). This object, most probably a fragment of comet, but just possibly an asteroid, is estimated to have been about 40 m in diameter. All other things being equal, anyone could have calculated that if a 40 m object travelling at cosmic velocity produces a 15 Mt airburst, then a 1000 m object should produce 15 000 times the energy (since volume is related to mass and mass is related to energy). In fact, because the objects were going to arrive at Jupiter much faster than the Tunguska object arrived at Earth, a factor of 15 000 would be a massive underestimate of the likely 1994 impact energies. So, we could reasonably ask who the people were who thought that the Shoemaker–Levy fragments would have 'no effects'? It was always pretty obvious that the impacts would be huge.

In general terms people who thought that impacts from space were mostly inconsequential were the products of earlier 20th century thinking. According to the vast majority of 20th century historical and archaeological researchers there is no evidence for anything from space having had any effect on human populations in the whole of the time since humanity became literate, i.e. the last five millennia. Obviously, if you live on a planet which has not been hit by anything in 5000 years, there is little to worry about in the less-than-a-century lifespan of a typical human. Presumably, by extrapolation of this thinking, impacts by comet fragments would be inconsequential. In July 1994 it was observed that the impacts on Jupiter were indeed huge, the largest releasing the equivalent of *millions of megatons*.

Shoemaker–Levy 9 acted as a turning point on the issue of impacts, and encouraged the development of a telescope survey to search for Near Earth Objects (NEOs) which are

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mostly Apollo asteroids, i.e. asteroids that cross the path of the Earth and hence pose at least a potential threat of impact. Here is how the initiative is described:

> The first phase—detecting 90% of the large (>1 kilometre diameter) Earth crossing asteroids by the end of 2008—is well underway, and seems to be well achievable. Of course this is only the start, and the next phase—detecting potentially hazardous asteroids down to a size of 140–150 metres—is going to be much harder. There are probably 300–350 000 of them and they'll be a lot harder to find. (Tate, 2006)

Currently the astronomers involved in the search estimate that they have found *all* the objects significantly greater than 1 km in diameter, and have located about 70% of the ca. 1 km objects. So the hazard posed by objects that might strike the Earth has now been recognised, and the first steps have been taken along the path of mitigation.

Excellent progress, one would think! Except that, although it is generally held that 1 km is the size of impactor that would cause a global catastrophe, many believe that an impact by a body down to 150 m diameter (yielding perhaps 750 Mt) would be sufficient to collapse the current global system because of the interconnection of the food, money, transport and insurance markets. Perhaps 'excellent' was too strong a term.

This space survey makes it look as if we are dealing with a mechanical universe, where asteroids in well-defined orbits can be neatly quantified and telescopic surveys can work towards mitigating risk. Unfortunately that is not the way things are in reality. Note that the fragments of Shoemaker–Levy 9 were most probably fragments of a broken up *comet*, whereas most of the NEOs are believed to be asteroids. Apollo asteroids are solid bodies, made mostly of rock or nickel-iron—deflected from the Asteroid Belt that lies between Mars and Jupiter—that have ended up in orbits that cross the path of the Earth. Comets are complex accumulations of frozen gases, water and other liquids with dust and mineral constituents, and we cannot rule out the possibility that some may include rocky cores. Comets can come into the inner Solar System from deep space, from any direction, and are inherently unlikely to hit a planet as small as Earth. However, they can be captured into short-period orbits, for example Comet Encke that orbits the Sun every 3.3 years, or Comet Halley that orbits every 76 years, effectively trapping them within our inner-Solar-System space environment. In addition, they tend to be loosely held together which is why comets have frequently been observed to split apart, under a variety of influences from thermal stress, to gravitational effects, to possible collisions in space. Some of the numerous comets that have been observed to split include Comet Biela (1846), Comet Wirtanen (1957), Comet Shoemaker–Levy 9 (1993), Comet Schwassmann–Wachmann 3 (1995), Comet West (1996), Comet Linear (2000) and Comet du Toit–Neujmin–Delporte (2002). Because they can break up, they end up as a population of fragments posing at least as great a hazard to Earth as true asteroids. Indeed, the fact that comets, or comet fragments, can lose all their surface volatiles and become dormant objects may explain why quite a number of so-called Apollo asteroids have orbital characteristics that bear more similarity to comets than to any object deflected from the Asteroid Belt with its restriction to the plane of the ecliptic (Asher *et al.*, 1993). Moreover, it has been suggested that many dormant comets may be so dark, because of their tarry coating of polyaromatic hydrocarbons—extreme albedo objects—that they may be essentially undetectable (Napier *et al.*, 2004). When these are added to the many small asteroids and comet fragments that cross the path of the Earth, our space environment appears to be very hazardous indeed.

The issue of craters and crater fields

While in general historians, archaeologists and palaeoecologists see no sign of any catastrophic impacts from space in the last 5000–6000 years, in their records, there undoubtedly are craters that have been formed during this time period. Table 1 lists 14 craters or crater fields from the last five millennia and makes no attempt to be complete. This provides us with a minimum number of impacts for discussion. Here are a few reasons why this is a *minimum* number for this time period.

1. 70% of the planet is covered by water so only land impact craters have been identified. For every 10 impacts on land there should be 23 on or over water—an issue that immediately introduces the question of tsunami frequency and cause.
2. Craters, especially small craters, are extremely difficult to identify as impact-derived. This is particularly the case because:
3. As a consequence of the lack of historical and archaeological interest, there is no paradigm for considering that circular lakes and ponds might be craters; few people are looking for craters.
4. Similarly, craters can be extremely hard to authenticate. For example, the famous Barringer Crater in Arizona, dating to 49 000 years ago, was caused by the impact of a lump of nickel-iron estimated to have been about 40 m across. It took many years of argument to establish that the crater was extraterrestrial in origin.
5. Recent craters are extremely hard to date accurately. Without good dating it is impossible to see whether an impact had any consequences that might have been recorded in historical or other records.
6. The Tunguska 1908 airburst tells us that not all impacts produce craters. Arguments continue as to just what the Tunguska object was. There is a persuasive argument that, because it arrived at the end of June, during the Taurid meteor stream, is was a largish fragment of Comet Encke (Clube and Napier, 1990).
7. When the craters and airbursts are plotted out, (see Fig. 1), it is apparent that vast areas such as Canada and Africa are more likely to be blank because of non-reporting, rather than zero impacts in the last five millennia.

To give just a taste of the problems, The undoubted Kaali craters are still not unambiguously dated to better than either 1500 BC, or ca. 800–400 BC (Veski, 2001). In the case of the undoubted Wabar craters in Saudi Arabia the suggested date

Table 1 Craters (or holes in the ground cogently argued to be craters)

Burghausen/Chiemgau, Germany (Fehr *et al.*, 2005; Rappenglück *et al.*, 2004)
Campo del Cielo, Argentina (Cassidy *et al.*, 1965)
Haviland, USA (Nininger and Figgins, 1933)
Henbury, Australia (Hodge, 1965)
Ilumetsä, Estonia (Raukas *et al.*, 2001)
Jilin, China (Bühler, 1988)
Kaali, Estonia (Veski *et al.*, 2001)
Kunya-Urgench, Turkmenistan (observed fall, 1998)
Sikhote-Alin, Siberia (Krinov, 1960)
Sirente, Italy (Santilli *et al.*, 2003)
Sobolev, Russia (Khryanina, 1980)
Sterlitamak, Russia (Ivanov and Petaev, 1992)
Umm al Binni, Iraq (Master and Woldai, 2004)
Wabar, Saudi Arabia (Bartrum, 1932)
Airbursts
Tunguska, Russia 1908 (Krinov, 1960)
Curuçá Brazil 1930 (Bailey *et al.*, 1995)

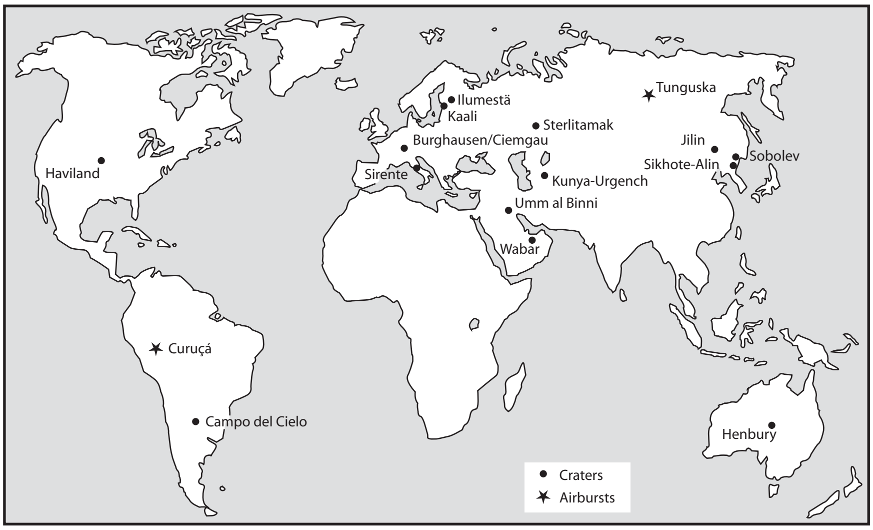

Figure 1 Distribution of known impact sites relating to the last 5000 years. Dots indicate craters; stars indicate airburst locations

range is spread over several thousand years. The Sirente craters in Italy have preliminary radiocarbon dates suggesting that these may have been formed between AD 300 and 600 (Santilli *et al.*, 2003). Unlike Kaali and Wabar, which are accepted as extraterrestrial in origin, the origin of the Sirente craters has been contested, with the suggestion that these circular, lake-filled craters are no more than artificial lakes for watering livestock (Speranza *et al.*, 2004). Similarly, the Burghausen/Chiemgau crater field in south Germany is still under discussion despite highly persuasive evidence for exotic chemistry at the site (Fehr *et al.*, 2005).

It almost seems that there is a reluctance to take craters seriously. Given their potential importance in assessing impact hazards, it is surprising that their identification is not afforded more importance by nation states; in general they are not regarded as national priorities and their study is left to the whim of individual researchers. Despite that, as shown in Table 1, there is reasonable evidence for at least a dozen craters on land within the last 5000 years. That would equate, allowing from the greater area of ocean, to a *minimum* of 40 notable impacts on the entire Earth's surface in this time interval. To that would have to be added a factor based on:

1 all the undiscovered craters in the vast wildernesses of the world, e.g. northern Canada, north Africa;
2 all the unidentified craters in the more developed world (owing to the reluctance to accept craters and the absence of a suitable paradigm), and
3 the number of non-crater-producing Tunguska-type airbursts. This latter is a very difficult number to gauge.

The airburst issue is exquisitely difficult. There are schools of thought that see Tunguska-class airbursts as anything from freak events, i.e. something likely to happen only once in thousands of years, to common events happening perhaps once every 50 years. Because within a century or so most airburst evidence will have been erased by vegetation, this is the great 'invisible hazard'. When we consider that Tunguska, and the example over Brazil in 1930 (Bailey *et al.*, 1995), were both over land, it is reasonable to surmise that there may have been another four or five over the oceans in the 20th century alone. The problem is that the only evidence for such airbursts might be tsunamis, which, if noted at all, would normally be attributed to tectonic causes. Lewis (1996) presents cogent arguments as to why the secondary symptoms of impacts will often go either unrecognised or misreported. These considerations illustrate the dilemma faced by those who believe there may be a significant impact threat to planet Earth. The number of recent craters is almost certainly underestimated; the number of airbursts similarly. Yet if we imagine that there could have been as many as five airbursts in the 20th century, and imagine that as a typical rate, then there could have been 250 airbursts in the last 5000 years. Such a thought makes it understandable why some people would prefer to regard Tunguska as a freak.

It has to be stressed again that everything militates against a realistic assessment of the numbers of impacts in recent millennia, be they crater-forming or airbursts. The lack of a suitable paradigm means that almost none of the hundreds of small circular lakes in, for example, the British Isles, have been investigated with impact origins in mind, yet Estonia has more than one Holocene crater field. What might a proper British survey reveal? To show what can happen, recently Master and Woldai (2004) drew attention to a 3.4 km diameter circular lake that appeared when a marshland area was drained in Iraq. The authors suggest the most likely date of the inferred impact was around 2300 BC, fitting it in with Courty's (1998) anomalous, and presumed extraterrestrial, layer of melted debris from Tell Leilan in Syria. If the impact case could be proved we might finally have an explanation for the widespread collapse of civilisation traditionally dated to around 2300 BC in the Middle East.

If we look for phenomena that might represent secondary effects of impacts, such as tsunamis, we find that Bryant (2001) has collected evidence in Australia for numerous tsunami events and goes so far as to suggest that there may be some extraterrestrial linkage:

> Six separate tsunami events can be recognised over the last 8000 years, with peaks at 7500 B.C., 5000 B.C., 3300 B.C. 500–2000 B.C., A.D. 500, and at A.D. 1500. . . . The peak of the A.D. 1500 tsunami event corresponds with the largest number of meteorite observations for the past two millennia. In addition, the peak at A.D. 500 corresponds with a clustering of meteor sightings that is believed by astronomers to be one of the most significant over this time span. . . . Both of these clusterings are associated with the Taurid complex. (Bryant, 2001)

Bryant's reason for imagining that some of his tsunamis may have extraterrestrial origins lies in his observation of 100 ton slabs of rock lifted onto the tops of 30 m cliffs on the Australian coast. He does not believe that any tectonically induced tsunami (barring mega-underwater landslides for which no evidence exists in the last 5000 years) could possibly be powerful enough to have caused these placements. Impact-induced tsunamis, on the other hand, have essentially no upper limits on energy yield. Looking at Bryant's list, two dates stand out, namely 5250 cal. yr BP (3300 BC) and 1450 cal. yr BP (AD 500). It is possible to lift other tsunami publications and find curious resonances. Bondevik *et al.* (2005) reported on two tsunami deposits in the Shetland Isles stratified above evidence for the ca. 8100 cal. yr BP Storegga Slide tsunami. The dates for these two tsunamis are given as ca 5500 cal. yr BP (ca. 3550 BC) and ca. 1500 cal. yr BP (ca. AD 450) a hint perhaps of things happening around the same times in both hemispheres. If we turn to unexplained tsunamis in the Atlantic, Ruiz *et al.* (2005) tell us that in southern Iberia at least 20 tsunamis have been registered in the last 7000 years. They draw attention to a high-energy, tsunami event in the 5400–5200 cal. yr BP (3450–3250 BC) range. In this context, it seems worth mentioning an anomalous silt layer observed by Caseldine *et al.* (2005) in peats on Achill Island in the extreme west of Ireland which is dated to 5200–5100 cal. yr BP (3250–3150 BC). In addition Baillie and Brown (2002) have drawn attention to an extreme tree-growth downturn at 3200 BC (5150 cal. yr BP) in Irish and other tree-ring chronologies which coincides with a series of effects from Switzerland to England to Greenland all suggestive of changes in the Atlantic regime. This is well exemplified by an observation by Zielinski *et al.* (1994) of an exceptional sulphate event across 5150–5100 cal. yr BP in the GISP2 ice core which they associated with the deposition of marine biogenic sulphate associated with open water in the permanent sea-ice off the Greenland coast. It seems reasonable to wonder whether all of these effects are related in some way and whether they might be explained by a cluster of impacts from space. Archaeologically 5150 cal. yr BP marks the transition from the early to the later Neolithic in the British Isles with a range of changes in site type, suggestive of human response to whatever was going on environmentally.

A more general point is that the historical and archaeological record is studded with abandoned sites, population movements and collapsed cultures. In few cases are the causes of such abandonments, movements and collapses known with any degree of certainty. Moreover there are true Dark Ages with little available written record, in particular the four-century-long Greek Dark Age between roughly 1200 and 800 BC, and the Post-Roman Dark Age spanning the fifth and sixth centuries AD. Nothing in archaeology, or history, rules out the abandonments, movements and collapses being the results of impacts, and the hypothesis has not been tested.

The astronomy of comet hazards

If you read astronomers on the issue of hazards from space it is possible to come away with quite different impressions. Sekanina and Yeomans (1984) conducted a statistical analysis of close comets and concluded:

> A collision rate of comets with the Earth ... implies an average period of time from 33 to 64 million years between two events . . . comparable with the frequency of geologically recent global catastrophes, apparently associated with impacts of extraterrestrial objects—the Cretaceous–Tertiary extinction 65 million years ago and the late Eocene event 34 million years ago. (Sekanina and Yeomans, 1984: 154)

—bad news, obviously, on geological timescales, but good news for a species that has only existed in large numbers for a few millennia. Of course, these authors were considering full-blown impacts with large comet nuclei, and consequent massive extinction events; these are indeed rare. This review article is about impacts that might have affected recent agricultural populations, that might have collapsed civilisations, that might have caused Dark Ages. Such impacts are in an entirely different class, and researchers who study the issues offer a very different perspective.

When comets come into the inner Solar System and are captured into short-period orbits (less than 200 years) they exhibit, as indicated above, a tendency to break up, producing fragments of a range of sizes. The result for an individual comet is an annulus of dust and debris, in the inner Solar System, in the trail of the comet. The key to these streams of debris is the annual observation of a series of discrete meteor showers as the Earth passes through the tracks of the parent comets. Thus we know the streams of debris exist, and those considering such issues point out that:

> if the larger (~10–100 metre) fragments happen to inhabit a mean-motion resonance with Jupiter, as is often observed to occur both in reality and in numerical integrations, then it is to be expected that a cluster of such objects will orbit the Sun grouped. . . .(Asher *et al.*, 1994)

Here we are confronted with a totally different view of potential hazards. We know that the Earth passes through the debris streams of comets; now we know that in those streams may lurk clusters of objects big enough to cause catastrophes. This clustering gives rise to a concept defined by Steel (1995) as 'coherent catastrophism'.

> as one considers larger particles, of sizes ~10–100 metres but also including some kilometre-sized bodies, cometary disintegrations lead to constrained clusters of such objects that will have repetitive intersections with the Earth when (i) The node is near 1 AU; and (ii) The cluster passes its node when the Earth is nearby. This would mean that impacts by cluster objects would occur at certain times of year, every few years . . . but only when precession had brought a node to 1 AU, and so on timescales of a few kyr. (Steel *et al.*, 1994)

This seriously researched view leads to statements such as:

> A few dozen sporadic impacts in the tens of megatons, and a few in the 100 to 1000 megaton range, must have occurred in the past 5000 years. (Clube and Napier, 1982)

Note the 'must'. So, there exists a school of cometary astronomers whose conclusions sit comfortably with the concept of numbers of damaging impacts during the existence of human civilisation. In a more recent paper Asher *et al.* (2005) have looked at the objects that are known to have come close to the earth in recent times. They conclude, based on various strands of evidence (for example, the number of meteorites discovered on Earth that originated on the Moon; hence the number of recent impacts on the Moon) that the average time between impacts on Earth is no more than 300 years, probably less.

The dilemma: why no records?

If serious numbers of impacts have indeed taken place in recent millennia, why have literate humans not recorded at least some

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of these impacts, and why have historians, archaeologists, and palaeoecologists mostly failed to find evidence for their effects? The question can be restated as follows: might some of these proposed impacts have given rise to some of the unexplained tsunamis, or the movements of human populations, or abandonments, or collapses of civilisation, or Dark Ages? Here we are forced to turn to the issue of *chronology*. The only reason we do not know the answer to this question is because hardly anyone can date their evidence with sufficient precision to make the necessary connections. Take the known Kaali impact in Estonia (Veski *et al.*, 2001). In an ideal world (obviously hypothetical) the Kaali impact would have thrown identifiable debris into a varved lake where the exact date of the varve containing the debris would have been established. Knowing the calendar date of the impact, we could check global tree-ring chronologies for relevant environmental effects. We could also interrogate the ice-core records and any existing human histories at that precise date to see if the impact was recorded, either chemically, or in writing.

In reality the best estimate of the date of the Kaali impact is around 800–400 BC, although ca. 1500 BC still cannot be ruled out (Veski *et al.*, 2004). It is therefore impossible to look in any of the other records in any meaningful way. So the impact undoubtedly took place, but the wider effects of the impact cannot be assessed because of the failure of chronology. We do not know if people reported 'signs' at the same time. This lamentable situation tells us why impacts are not identified in historical sources. If we knew the *dates* of impacts we might find that coloured skies or abnormal weather or earthquakes or tsunamis were recorded at the same time; all potential symptoms of an impact. Without the dates, coloured skies are aurora, abnormal weather is just that, and earthquakes, and tsunamis, are tectonic. It may be the case that secondary effects of impacts are there in the record but they cannot currently be interpreted. If this is the situation with historical sources, almost by definition the situation with archaeology must be worse. Few archaeological sites can be dated to calendar years and, unlike history, there is no continuous annual archaeological record. The same can be said for Holocene environmental research: chronological limitations almost preclude the investigation and interpretation of impacts.

With the limitations of the environmental, historical and archaeological records, what sources are left to us? The answer is self-evident. The only other records with really good dating control are tree-rings, ice cores and, just possibly, mythology.

Can we deduce impacts from tree-rings and ice cores?

Surprisingly it may just be possible; the logic is quite simple. If trees on a large scale show a pronounced growth reduction we can infer an environmental cause. If trees globally show reduced growth we can infer that something reduced the amount of solar radiation reaching the Earth's surface. There are a limited number of vectors that can reduce sunlight, namely a reduction in solar output or a dust veil. Dust veils can be either volcanic or extraterrestrial in origin. This is where it may be possible to use tree-ring and ice-core evidence to narrow down the possibilities. Take the well-documented case of the happening around AD 540. Trees from across northern Eurasia (Fig. 2), Europe (Fig. 3), North and South America show markedly reduced growth in the time window AD 536–545 (Baillie, 1994, 2001). There are historical records of the Sun being dim in AD 536–37 interpreted by Stothers and Rampino (1983; Stothers, 1984) as a 'dry fog' or dust veil. The first suggestion, therefore, was that the global tree-growth downturn was probably due to a volcanic dust veil. Indeed this idea was taken to its logical conclusion when Keys (1999) proposed that the event was due to a super-eruption of Krakatau in February 535—a suggestion for which there is no actual evidence. One test of Key's suggestion is whether there is a major layer of acid at or following AD 535. Large volcanoes are normally registered in the annually banded Greenland ice records, principally as layers of sulphuric acid. The European ice-core workers now have four replicated Greenland ice cores across the last two millennia, namely Dye3, GRIP, NGRIPa and NGRIPb (Clausen *et al.*, 1997; Vinther *et al.*, 2006). With this level of replication they are now confident that their dating, back in the sixth century, is to ± 1 year, and they state that the only large acid signal in their ice record in the vicinity of AD 536–545 is in the late 520 s (Larsen *et al.*, 2002). Thus, the global environmental event registered by the tree-rings seems not to have been caused by a volcano, certainly not by a

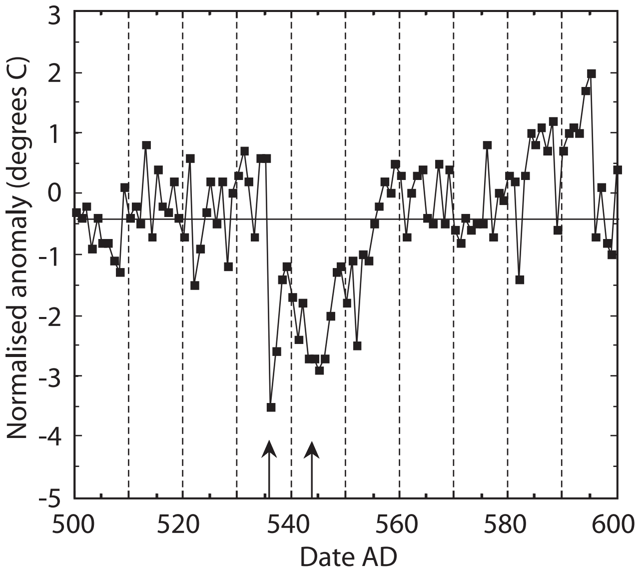

Figure 2 Reconstructed temperature anomalies (combined) from tree-ring chronologies from Tornetrask (Sweden) and Yamal and Taimyr (Russia) showing the most extreme temperature reduction in the last 2000 years at AD 536 and 544 (arrowed) (after Briffa, 1999)

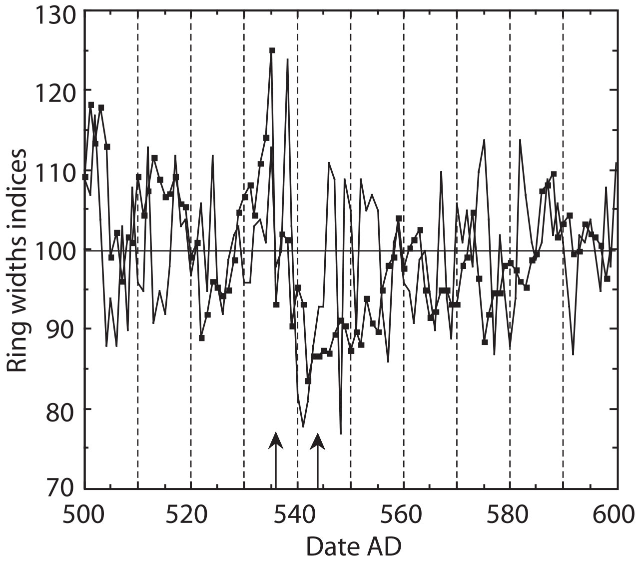

Figure 3 Tree-ring chronologies for Irish oak and Finnish pine (Zetterberg *et al.*, 1994) showing the same AD 536 and 544 growth reductions as in Fig. 2

super-volcano. It is this negative evidence which allows consideration of a second possible cause of the AD 540 environmental event, namely loading of the Earth's atmosphere from space (Baillie, 1994, 2001).

As soon as the question was posed about atmospheric loading from space around AD 540 it was observed that Gibbon mentioned a comet in AD 539:

> [it] appeared to follow in the Sagittary: the size was gradually increasing; the head was in the east, the tail in the west, and it remained visible above forty days. The nations who gazed with astonishment, expected wars and calamities from their baleful influence; and these expectations were abundantly fulfilled. (Gibbon, 1832)

While a medieval English historian, Roger of Wendover, mentioned:

> In the year of grace AD 541, there appeared a comet in Gaul, so vast that the whole sky seemed on fire. In the same year, there dropped real blood from the clouds, and a dreadful mortality ensued. (Britton, 1937)

It seems that, as noted above, if precise dates can be obtained for events then sense can be made of previously unregarded comments and descriptions. This is also the place to mention that immediately after AD 540 the first Great Plague of the present era broke out—the plague of Justinian—that claimed perhaps one-third of Europe's population. It became increasingly clear that the environmental event defined by the tree-rings was a major environmental event with catastrophic consequences for human populations, an event, moreover, which might have been caused by loading of the atmosphere from space, most probably by some interaction with a comet. Is such a thing possible? Rigby *et al*. (2004) made some calculations on the size of impactor that might be necessary to cause the AD 540 global environmental effects and concluded that an impactor about half a kilometre in diameter would have been sufficient. Presumably if a single impactor in this size range could cause a global environmental downturn, a shower of smaller impactors could have equivalent effects.

Supporting evidence of an unusual kind

With such a scenario constructed for the AD 540 event it is interesting to see what else is available, short of the location of extraterrestrial material in a sealed and dated context. Two things are worth mentioning. It transpired that, in two publications on comets, Bailey, Clube and Napier (1990: 75–76) and Clube and Napier (1990: 258) had hypothesised that because of precession and because of the large number of major meteor showers recorded in the period, the time window AD 400–600 might well have been a specific period of risk of bombardment by comet debris. They even used a graphic descriptive term for the sort of bombardment event they were contemplating, namely a *cosmic swarm* by which they mean a large number of Tunguska-class impacts in a short period of time. From a scientific viewpoint, comparison of these 1990 astronomy publications with the 1994 tree-ring publication dealing with the AD 540 event (Baillie, 1994: 216) seems to show a prior scientific hypothesis fulfilled, viz. Bailey, Clube and Napier had proposed AD 400–600 as a period of risk and a completely independent worker had asked if the AD 540 tree-ring event might have had an extraterrestrial cause. This independent fulfilment of a published prior hypothesis should carry some weight with scientists.

The second issue, despite being anathema to most scientists, has to be mentioned. If the AD 540 event had an extraterrestrial cause, it has to be interesting that the death of the Celtic deity 'King Arthur' traditionally falls just at that time (he is variously thought to have died in AD 537, 539 or 542). It is not hard to find in the literature that Arthur is cognate with other Celtic deities, namely Lugh, CúChulainn, Manannan, Mongan, Finn, etc. (Loomis, 1927; O'Rahilly, 1946). When Lugh is described in one story as 'coming up in the West, as bright as the Sun, and with a long arm' the idea of a comet seems fulfilled (McCafferty and Baillie, 2005). Another story involves the Celtic deity Mongan and his escape to the Otherworld in AD 538 (Stephens, 1923). Mongan is the 'son' of Manannan and the 'rebirth' of Finn and he is eventually killed by a Briton named Arthur, a clear demonstration of the linkages in the mythological stories (D'Arbois de Jubainville, 1903). In this Mongan story we have a *dated* myth telling us about terrible showers at the same time as the death of a comet god, just at a time that tree-ring chronologies indicate a global environmental event, just when the ice-core records tell us that a volcano was *not* involved, just at the initiation of a major plague. So, mythology points a clear finger at the period around AD 540, just as global tree-ring records do. When it is considered just how thin the historical record is, worldwide, around AD 540 we may in fact be looking at cause and effect—truly catastrophic events leaving few records except myth which is fundamentally an oral tradition.

Discussion

Readers now know enough about the background to this impact issue to have a sense of the interdisciplinary nature of the work necessary to tease out answers. It is not a mechanical analysis of a sediment core or the modelling of glacial flow, rather, it is a blend of archaeological science, history, astronomy and mythology bound together with some chronological glue. Without the AD 540 tree-ring dates for the environmental event, none of the rest of the picture could be understood. Now, with the date defined, and its cause suspected, new pieces of

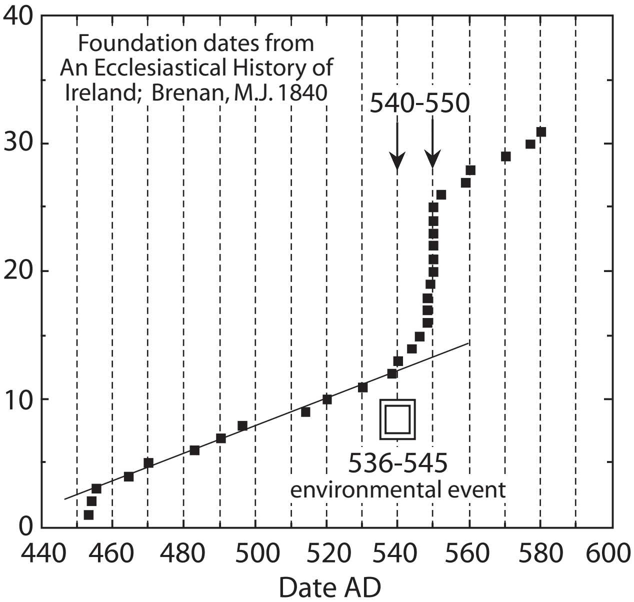

Figure 4 Cumulative plot of the dates of religious foundations in Ireland indicating a memory of the AD 540 event

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evidence can be uncovered. One example is the distribution of traditional church foundation dates in Ireland (Brenan, 1840). Plotting these through time (Fig. 4) indicates that the Church in Ireland retained a memory of the decade of the AD 540s as a new beginning (McCafferty and Baillie, 2005). Another, from Japan, relates to the *Enoshime Engi* (the History of the Enoshima Temple). It was written in AD 1047 and mentions some happenings just prior to the arrival of Buddhism in Japan, the traditional date for which is AD 538 (Aston, 1956). It appears that there was an apparition of the bright goddess Benzaiten who looked 'like an autumn moon enveloped in mist'. She was adorned with a long jade pendant and as she descended she was accompanied by a myriad spirits of dragons, fire, thunder and lightning that made 'great boulders descend from above the clouds'. She arrived after an episode 'when dark clouds covered the sky and the earth quaked continuously for 11 days'.

Given that in Irish myth Mongan went to the Otherworld in AD 538 to avoid the 'terrible hailstones' just after the sky went dark it seems we have two contemporary descriptions of dark skies and things falling from the sky at opposite ends of the Old World at the same time. It could be asked whether something that looks like 'an autumn moon enveloped in mist' could be a description of a relatively close comet? However, we do not have to rely on mythology or church history. It turns out that there is some other well-dated information from the ice cores.

When it became apparent that the replicated ice cores offered dating almost as precise as tree-rings, another look was taken at the available chemistry from the GRIP ice core. It was quickly established that the ammonium (NH_4) record was of more than passing interest. In the GRIP record the analysis of ammonium was carried out of 55 cm lengths of core (thus, for example, each length represents approximately 2.5 years of ice back in the sixth century) (Fuhrer *et al.*, 1993). The background concentrations of ammonium vary around 6 ppb. At a depth of 336.325m—equating to AD 539—there is an ammonium spike of 35 ppb which is the second-highest value in the core between 150 BC and AD 1642. What causes a large concentration of ammonium in the ice? The generally accepted explanation is 'biomass burning' or forest, or grassland, fires (Legrand *et al.*, 1992; Taylor *et al.*, 1996). However, it is known that ammonia occurs in comets. Lyttleton was suggesting this as early as 1953, while Wickramasinghe (2001) stated that the presence of the amino group (NH_2) in the emission bands of cometary coma and tails also made it reasonable to assume the presence of ammonia. More recently ammonia was detected directly in Comet Hale–Bopp at 1–2% concentrations (Bird *et al.*, 1997). This means that the presence of ammonium at AD 539 in the ice is in no way inconsistent with the comet impact hypothesis.

The observation of ammonium at AD 539 raised a further question about the even larger concentration of 46 ppb at depth 238 m, equating to a date centred on AD 1014. Given the issues around AD 540 of ammonium, comet and myth, it has to be of interest that AD 1014 has references to an unusual cloud:

> 1014 Short refers to a remarkable calamity in this year. He says 'a heap of cloud fell and smothered thousands'. He adduces the Anglo-Saxon Chronicle as authority for this phenomenon, a work in which there is certainly no mention of it. It might conceivably be a poetic distortion for a heavy rainstorm in which many people were drowned. (Britton, 1937)

There is also another reference to an unusual happening this year which again would not be inconsistent with an impact over the Atlantic:

> 1014 Severe Marine inundations on September 28
>
> Anglo-Saxon Chronicle: And in this year on St Michael's mass eve came the great sea flood widely through this country, and ran so far up as it never before had done, and drowned many vils [*places where people live*], and of mankind a countless number (this author's inserted italics). (Britton, 1937)

Thus immediately upon observing the date AD 1014 some possible sense can be attributed to pre-existing references in the literature. Surprisingly, it was also possible to find a Chinese mythical story set 'after late 1012' in which a sky god named No-Cha—who bears remarkable similarities to the Irish god CúChulainn—is sent down by the Lord of Heaven (Walters, 1995). Then, from a scientific standpoint, Sekanina and Yeomans (1984) list AD 1014 as a year when a comet (C/1014 C1) made a relatively close approach, passing within just 0.04 AU of the Earth. So, as with the episode around AD 540, we have ammonium, a close comet and a descending sky god myth around AD 1014, with an inundation thrown in for good measure.

It was then observed that there is a large concentration of ammonium in the American GISP2 ice core at the time of the Tunguska impact. To clarify, while the GRIP core was analysed in 55 cm sections, from AD 1642 back to around 850 BC, the American GISP2 core was analysed at different resolutions. The available, high-resolution, GISP2 record is discontinuous, but with a little searching it is possible to find that, at 33.3404–33.4034 m depth there is a large spike of ammonium (Mayewski *et al.*, 1990). This depth equates to AD 1908.48, quite remarkably consistent with the June 30 1908 Siberian impact. The American analysis shows us that, irrespective of the mechanism involved, a high-energy event in the atmosphere seems to have led to a significant amount of ammonium being deposited in the ice record. So, if Tunguska caused an ammonium anomaly in AD 1908, then, when we go back to AD 1014 and 539, impact events have to be a *possible* explanation for the large ammonium spikes there. To elaborate on AD 1908: there were also high levels of chlorine, nitrate (nitric acid) and sulphate (sulphuric acid) in exactly the same layers of ice; indeed, it has been estimated that the high-energy impact event generated 30 million tons of nitric oxide in the atmosphere. In turn, this has been shown to have annihilated about one-third of the Earth's protective ozone layer (Turco *et al.*, 1981). All of this allows speculation on the nature of the Justinian 'plague'. Could loss of ozone, and loading of the atmosphere with a chemical 'soup' have been the actual cause of the so-called 'plague' following AD 540?

Now that we have a case for impacts producing ammonium at AD 1908, 1014 and 539, are there other possible instances? It so happens that in 2004 astronomer Peter Jenniskens published a paper wherein he proposed that the Quadrantid meteor shower (which normally peaks on 3 January each year) originated from a minor planet named 2003 EH. This object, which was discovered in 2003, was in a high-inclination, comet-like orbit that fits with the orbit of the Quadrantids. By projecting the orbits back in time, Jenniskens found that: '. . . we cannot exclude that (comet) C/1490 YI was a prior sighting of the Quadrantid parent at the epoch when it created the shower'. So Jenniskens drew attention to a comet partially disintegrating in AD 1490–91. Reference to the American GISP B ice-core chemistry record (Mayewski *et al.*, 1990) shows that at a depth of 144.12 to 144.55 m there is *both* elevated ammonium and nitrate. This layer dates between AD 1490.4 and 1491.9 (centre date 1491.15). Indeed these are the highest ammonium values between AD 1429 and 1536 and

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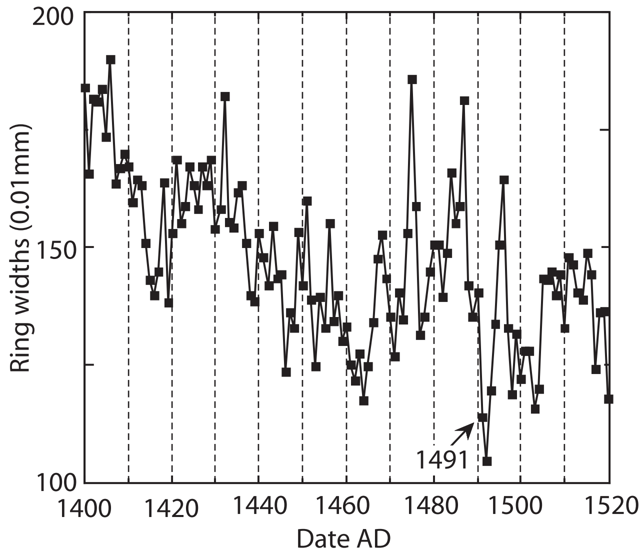

Figure 5 Mean ring-width chronology for European oak, from eight sites spanning Ireland to Poland, showing the notable growth depression in AD 1491–92

the highest nitrate values between AD 1427 and 1617. However, just in case C/1490 YI did not produce the ammonium signal in the ice, Sekanina and Yeomans (1984) inform us that the *closest known* approach of a comet was in AD 1491, namely Comet C/1491 BI which passed within a mere 0.0094 AU (1.4 million kilometres) of Earth on 20 February 1491. Figure 5 shows a major decline in the growth pattern of European oaks in 1491–92. Overall, it looks as though at least some of the ammonium spikes in the Greenland ice really might be signatures of extraterrestrial bombardment by comet debris.

Conclusion

It is increasingly evident that intellectually the world is divided into two. There are those who study the past, in the fields of history, archaeology and palaeoecology, and see little or no evidence for any human populations ever having been affected by impacts from space. In diametric opposition to this stance there are those who study or take an interest in the objects that come close to, and sometimes collide with, this planet. The latter group appear to be willing to look at a wider range of evidence than the former. When myths come with dates, why should they be ignored? What are the chances that someone looking for evidence of impacts would come up with the dates AD 1014 and 1491 purely on the basis of the presence of ammonium, and subsequently find that these are the dates of two of the closest comet approaches in Sekanina and Yeomans' 1984 list? What are the chances, given the way the latter dates were discovered, that AD 539, 1014 and 1491 should be at 475/477 year intervals-is this a hint of periodicity? There is, without doubt, enough interlinking information, from a variety of disciplines, to suggest that there is a major story involving ammonium, comets and myths. One final link may suffice to make the point. There is ammonium in no fewer than four ice cores at AD 1348, a date that marks the arrival into western Europe of the *second* 'Great Plague' of this era (Baillie, 2006). Ammonium at the start of the two great plagues . . . makes one wonder . . . especially as Hughes (2003) notes a change in the frequency of comet sightings around AD 500 and again around AD 1350.

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