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Narrative Report on the Hazard to Civilization due to Fireballs and Comets

by S.V.M. Clube

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1. Unforeseen Hazard

The ~ 100,000 year average interval between asteroid strikes (Chapman & Morrison 1994) first became apparent during the 1970s. Another discovery of considerable moment about this time was that of object Chiron. Considered to be a "giant comet" and found to be moving in a chaotic orbit beyond Saturn close to the ecliptic (Kowal 1979,Oikawa & Everhart 1978), the possibility of its future transfer to a more stable sub-Jovian orbit capable of penetrating near-Earth space and hence threatening the Earth was also soon recognized (Bailey et al 1994, Steel et al 1994). ***Indeed, whether or not Chiron is the next source of danger to the Earth, the disintegration of an exceptionally massive, comparatively fragile object in near-Earth space is now firmly in prospect - and probably within the timescale of the next asteroid strike.***

The implications of this disturbing fact are only now beginning to be fully appreciated. Thus a disintegrating giant comet in near-Earth space will transfer dust and detritus to the terrestrial atmosphere, affecting the climate (see later), with the result that the Earth is very likely once again to be locked into an ice-age (or glacial) lasting tens of thousands of years. This alone could be considered hazard enough (before the next asteroid strike) but in drawing attention to how the next glacial will probably start, Chiron has also caused us to recognise how the last glacial probably ended. ***The point here is that whereas the less fragile debris of a giant comet will eventually cease to erode and a glacial will eventually cease to be maintained, so the Earth will be restored to an interglacial, such***

as now, along with a heirarchy of orbiting remnants from the latest giant comet to be passing through near-Earth space.

Although most of these remnants are too small to be seen in space, even with the benefit of 20th century technology, their presence is readily enough betrayed by the zodiacal dust which continues to accumulate in the ecliptic and by the rather sudden encounters which the Earth makes every other century or so, for several decades, with orbits containing fresh concentrations of debris. These encounters produce an overabundance of fireballs penetrating the Earth's atmosphere implying both an increased probability of bombardment by sub-kilometre debris AND an increased risk that the Earth will penetrate the core of a minor disintegration stream à la Shoemaker-Levy. ***These encounters are also a previously unforeseen hazard in modern times and re-present a formidable insult to the terrestrial environment - one with which civilization is now having to come to terms.***

Curiously, the bare nature of the insult described here (sustained dust and fireball bombardments from space, commonly interpreted in the past as a prelude to "last times") was not immediately recognized in the United States. At the end of the Cold War, indeed, when a series of meetings at San Juan Capistrano, Tucson and Erice was convened to examine the celestial hazard to civilization under the partial sponsorship of NASA and BMDO (formerly SDIO), the available studies of the giant comet hazard were seriously under-represented. As a consequence, both the Spacewatch and Spaceguard programmes originating from America were largely organized with reference only to anticipated asteroid strikes and hardly at all with reference to the historically oppressive disintegrating comets. The omission was thrown into sharp relief at the final meeting by the timely break-up of Comet P/Shoemaker-Levy 9 and its subsequent bombardment of Planet Jupiter. It required only a modest degree of lateral thinking to recognize that the Earth might be the next in the line of fire from a disintegrating comet. Already, in fact, the possibility of a frequently recurring comet/fireball hazard to civilization due to the most recent giant comet to dominate Jovian and sub-Jovian space, ie during the late Pleistocene and subsequent Holocene, was envisaged (Clube & Napier 1984, 1990; Asher & Clube 1993). ***The present project, by way of an assessment of the comet/fireball hazard to civilization, supported at BMDO by Dr S.P.Worden and Dr S. Nozette, was initiated accordingly.***

This report (based on 3 papers for mainstream scientific journals arising from the project), recognizing that the US military now monitors the background global influx of meteoroids producing kiloton-plus fireballs (Tagliaferri et al 1994), details the essential background of knowledge relating to the likely most conspicuous source of this influx. Particular emphasis is placed on the sudden enhancements of this influx every other century or so. Of these, at present, we have no accurate foreknowledge. This is a somewhat tantalising situation for twentieth century man since there is good reason to suppose the enhancements have been powerful historical determinants dictating the rise and fall of civilization(s). In fact, it seems that large enough impacts due to asteroid strikes may indeed settle the fate of mankind but the fear of smaller impacts during fireball bombardments may settle the fate of civilization(s) much more frequently. ***The problems relating to the celestial hazard, in other words, are a good deal more subtle and urgent than hitherto supposed.***

The report then is by way of being a flier delineating the current state of research (historical and scientific) concerning the cometary and fireball threat. While it should be clearly understood that the present author does not discount enterprises such as SPACECAST 2020 and the planned searches for NEOs, there is already some evidence in the public domain for a grossly over-simplified view regarding the nature of the prime hazards from space. In fact, the complexities of the celestial hazard are by now well documented in the scientific literature and call for more than a limited military/scientific response concerned purely with the rarest and largest events. ***It is desirable that US Congress and US Space Command do not remain uninformed.***

2. Historical perspective

The whole of mankind was clearly reminded of a potent Solar System force when the fragmentation debris of Comet Shoemaker-Levy bombarded Jupiter in July 1994. Individual explosion energies ~ 10 million megatons of TNT equivalent, had they occurred on Earth, were plainly sufficient to have wiped out civilization and hand over control of the planet to another species. The response however was mixed, albeit most nations of the world looked for their lead to the United States. While some sections of the US Administration (possibly influenced by BMDO) openly contemplated strategies and procedures for deflecting such a danger should it apply to the Earth, other sections of the US Administration (possibly influenced by NASA), like many other national governments

around the world, selected to turn a blind eye to these dramatic events in the Solar System's backyard. Such attitudes clearly represent an extreme divergence of views but since there has been no obvious consequence to hand, the situation has passed without further comment. Such attitudes however have been commonplace amongst national elites in the past and do not auger well for the global village in future. ***Thus, we have no idea whether national elites during present or future times of cosmic bombardment of the Earth will be able to forge any kind of agreement on an appropriate timescale out of such extreme divergences of view.***

The point here is that there have been five extended epochs since the Renaissance when the Earth apparently encountered the fragmentation debris of previously unsighted comets. During these epochs, broadly coinciding with the Hundred Years' War, the Reformation, the Thirty Years' War (including the English Civil War), the French Revolutionary Period (including the American War of Independence) and the mid-nineteenth century Revolutionary Crisis in Europe, the various national authorities could do very little to restrain public anxiety in the face of the perceived danger. The fact of a perceived danger at these epochs, signified historically by a global rise in eschatological concern, is now understood in various academic quarters as marking some kind of physical dislocation (climate? disease?) which causes economic and social activity to be widely deranged, even to the point of collapse of civilized society, leading then to revolution, mass migration and war, amplified on a global scale. The occasions of such breakdowns in civilization are of course a matter of serious concern and their systematic study has been taken up in America (and elsewhere) at such institutes as the Center for Comparative Research in History, Society and Culture at the University of California, Davis (Goldstone 1991). To the "enlightened" however, the eschatology remains an anomaly and secure connections with celestial inputs have generally still to be made. ***We should recall however that many, as usual on these occasions of breakdown, would see "blazing stars threatening the world with famine, plague and war; to princes death; to kingdoms many curses; [and] to all estates many losses....."***

The three earliest of these epochs are of course the periods of Inquisition and of the great European witchhunts (which spilled over to America) when ecclesiastical and secular administrators alike would discourage any (astrological) notion that the celestial sphere interfered with terrestrial affairs. The separate stories of scientific revolutionaries like Copernicus, Kepler, Bruno, Galileo and Newton now bear witness to the ferocity with which the most acceptable cosmic viewpoint (of the time) was imposed. Indeed these

separate stories are still being adjusted and Newton, it is now realised, was constrained by his times to work under conditions of rather considerable censorship. The acceptable part of his scientific output was of course published and has proved its worth repeatedly over 300 years. The unacceptable part however dealt with "blazing stars" and eschatology and remained unpublished for some 250 years. One of the first to examine this material (Keynes 1947) was so taken aback by the contrast as to dub Newton not so much "the first of the age of reason" as "the last of the magicians, the last of the Babylonians and Sumerians". Thus it was the Founding Fathers of the Royal Society in Restoration England who hit upon the 'enlightened' step of deriding the cosmic threat and public anxiety; and it is not without significance today that English-speaking nations ultimately stood firm and prospered as others faltered at the last and briefest of the above epochs (Goldstone, loc cit). ***Accordingly it is largely an Anglo-Saxon 'achievement' that cosmic catastrophes were absolutely discarded and the scientific principle of uniformitarianism was put in place between 200 and 150 years ago.***

These epochs of eschatological concern are generally well traced at the national and continental level but tend to be less securely correlated at the international and global level. In America, for example, there is an extensive and very rich literature describing the build-up and decline of eschatological concern, prior to and beyond the War of Independence, during the penultimate and perhaps most significant of these epochs (ie so far as 20th century civilization is concerned). Thus the closing decades of the 18th century were a period of intense intellectual ferment and revolutionary zeal such as had previously afflicted European (and American) society during the central decades of the 17th century (eg Trevor-Roper 1987, Thomas 1971, Ball 1975): they correspond to the last major outbursts of doomsday prediction and its customary millennialist response. The factual component behind these outbursts was of course the possible drastic input from space in parallel with the observed "blazing stars" and the extreme states of foreboding and hope which these circumstances inspired. What is perhaps remarkable about the 18th century in particular is its characterization near the turn of the century, especially in America, by secular modes of thought (eg Bloch 1985) which meant that millennialism was replaced by utopianism while doomsday prediction came to be regarded as a mindless extravagance. Thus did mankind, stranded between zealotry and incomprehension, settle on a basically uniformitarian perception of its future celestial environment just as supernaturalism could no longer be entertained as an explanation of the terrestrial record. The uniformitarianism-catastrophism issue came of course to be hotly debated at this time during geology's emergence as an independent science. That uniformitarianism remained

in place however owed as much to public opinion - as much in America to the new milllennialist (or utopian) dream - as it did to science: thus the scientific debate was only reconciled towards the end of the 19th century when the sequence of major events in Earth history was adroitly perceived not so much as catastrophic as *episodic* (Hallam 1989). Increasingly though, we now know that the geologists dissembled: the episodes of catastrophes are a *periodic* galacto-terrestrial imprint (Clube & Napier 1996). ***It is the successive giant comets in near-Earth space dislodged from the huge cometary cloud accompanying the Sun in its epicyclic orbit around the Galaxy which essentially control these periodic events on Earth. It is the successive giant comets in near-Earth space, in other words, which happen to control biological evolution on Earth: it is the last and next giant comets in near-Earth space which are of the most immediate concern to civilization and mankind.***

By now, indeed, the Space Age has exposed the intellectual fault-line which separates public (uniformitarian) and scientific (catastrophic) opinion. It is a paradox of course that the Space Age may owe its very existence to a perceived uniformitarian condition which put no bounds on a nation's enterprise and enlightenment, only to have it reveal an environment which is not at all that which was dreamed! However, a realignment of perspective is already well under way in the Earth sciences. In the physical and astronomical sciences, events on the scale of the human environment are perhaps still overshadowed to a degree by developments at the very smallest and very largest scales. But here, the moneyspinners have now rumbled the essentially unbounded nature of much particle physics and cosmological research and it is now simply a question when the protectors of the public purse will recognize the celestial hazard on the timescale of human interest of past and future concern. ***Thus, as we breast the uniformitarian slopes, mankind has yet to come to terms with a celestial hazard issue which is highly interdisciplinary, of immense socio-political significance and still almost wholly unexplored.***

3. Paradigm Shift

Until recently, the perception of the interplanetary environment as hazardous on human timescales was not widespread. In a 1982 book on comets, the astronomers Brandt & Chapman stated that one expects a Tunguska-like or multi-megaton impact about once in 2,000 years, the devastation from which would be purely local. Their

comment that "No one should lose much sleep over this situation even if agitated by uninformed doomsayers" reflected the general view. As recently as 1990, in their book on the interplanetary hazard, Clube & Napier (1990) commented that "The astronomical community has so far shown little awareness of the potential human consequences of even a single impact". Thus in history (as until recently in geology) it has been possible to adopt the view that human culture and history evolve in parallel with purely Earth-based processes (climatic change etc.) rather than in parallel with significant extraterrestrial inputs. Since 1994 perceptions in Solar System astronomy have changed dramatically, and it is now almost universally accepted that impacts from small bodies have occurred and do pose a significant hazard for mankind (eg Gehrels & Matthews 1994). However to date the human implications of this altered perception have not been widely probed.

Until 1994, discussion of detection and deflection strategies were predicated on the assumption that the most significant hazard is posed by stray Earth-crossers from the main asteroid belt. However in terms of mass influx, the inner planetary system is essentially dominated by giant comets, mostly arriving in Earth-crossing orbits of low (Chiron-like) inclination but also in high (Kreutz-like) inclination to the ecliptic (Bailey et al. 1994). Sporadic flooding of the inner planetary system by the disintegration products of these rare bodies yields a risk assessment which differs from that of the 'stray impact' scenario both qualitatively and quantitatively. Aspects of this process - the unforeseen hazard of Section 1 of this report - were illustrated by the multiple fragmentation and subsequent Jovian impacts of Comet Shoemaker-Levy 9 in July 1994.

Essentially, then, there are two types of Earth-crossing interplanetary body: asteroids and comets. In broad terms asteroid impacts may cause destruction over continental dimensions at intervals of about a hundred thousand years, while the dispersed fragmentation trains of comets (comprising meteoroids about a metre to a kilometre in size) are encountered much more frequently, several times over a number of decades at intervals of a couple of a centuries or so. The result is airburst bombardments which are easily detected above the background fireball flux (monitored nowadays by surveillance satellites) and a more or less continuous stratospheric dusting which may also rise to a very high level during these bombardments. At intervals of a century or so therefore the enhanced fireball flux is capable of including large meteoroids with the potential individually to produce impact damage on the scale of a small country ('super-Tunguskas') and/or significant global damage through a sudden deterioration in climate ('mini-ice ages'). Historically, these bombardments were recognized as 'blazing stars' or

'providences' and it was usually the astrologically minded 'doomsayers' and the ecclesiastically minded 'soothsayers' who would initially be concerned about the more serious celestial threat (Clube 1996; cf Thomas 1971). The problem in antiquity, as always, was to ensure that this concern did not get out of hand.

The nature of the concern is clear. Thus the enhancements of the fireball flux imply a greatly increased risk (1 in 10 or so) that the Earth will encounter a Shoemaker-Levy like train of super-Tunguska debris. The potential then is for a multiple impact hazard of about 10,000 megatons while those bodies which break up at high level during their approach to Earth may, in addition, produce a darkened sky for perhaps a decade with a consequent failure of agriculture etc. (see appendix A for a fictional account of this kind of global catastrophe in a contemporary context). The combined hazards in fact represent a terrifying prospect and for a realistic representation of what this currently means to mankind, one can perhaps imagine BSE, AIDS, flood, nuclear bombardment, earthquake, plague, global warming etc all rolled into one and coming next week. Such threats fortified by expert opinion are clearly testing beyond the norm and unprepared national administrations can certainly be expected to break down and add to the mayhem - even without an impact! ***Based on the available records therefore, we now recognize a particularly drastic hazard which is roughly 1000 times more likely to occur than an asteroid strike, albeit the threat will actually be realised only about 100 times. In any case, this additional threat will pale to insignificance if a new giant comet intervenes and causes a new ice-age.***

If there is a problem concerning the hazard from space at the present time, it is that nearly everyone engaged in contemplating the celestial threat has developed a highly clinical a view of what is going on. Thus the commonest threat from space derives not from asteroids but comets and the patient (mankind) is interactive rather than anaesthetized. The enhancements of the fireball flux will continue to be observed. Indeed, unless nations are prepared for the hazard, the elements of uncertainty in the final prediction, which are bound to exist, will continue to generate chaos at the point of celestial interaction and the human response will be incapable of other than magnifying any physical impact damage. In all likelihood, we are addressing a situation here in which mankind will survive but in which the breakdown of civilization may well be complete and will recover only by the restoration of feudal management. It is an interesting new question therefore whether the application of 20th century know-how can save modern civilization this ultimate indignity. I dare say our grandchildren would say it should.

However, if we pursue this line of argument to its logical conclusion - and history, as we shall see, demonstrates that we must - technology will probably have to be developed to eliminate all bodies > 10 metres approaching the Earth, sooner rather than later.

The point here is that when the prospect of these global catastrophes recurs, such is the nerve-racking tension aroused in mankind that the principal leaders of civilization have long been in the habit of dissembling as to their cause (and likelihood) simply in order to preserve public calm and avoid the total breakdown of civil affairs. European civilization appears to have originally modelled itself in this regard in accordance with Plato's guidance in the *Timaeus* which describes not only the bombardments but the necessary elements of sophistry to be displayed by governments. The source of these bombardments, expressed in non-secular terms, was of course a divine creation: a "heavenly" circulation (of high eccentricity) which was inclined to the planetary "firmament". Throughout history on the other hand, there have also been advanced civilizations which have succumbed to their own propaganda and which have rewritten history so as to expunge the record of previous disasters and the occasions of greatly enhanced risk! The modelling in this respect was then more in accordance with Aristotle's advice and his highly sophisticated but erroneous scheme for the cosmos which attributed only an essential (but harmless) role to the planets. The result in medieval Europe, it would appear, was a heavenly circulation attributed unpredictable and quintessential (ie aethereal) characteristics by catholic "sophisticates" (from Aquinas down to the Jesuits) who were eventually defied by Galileo and laughed out of court by the protestant "down-to-earths". The latter of course prided themselves on having ushered in modern science during the 17th century but then developed their own sophistry when they ushered out the heavenly circulation (to re-emerge in the 20th century as the Taurid Complex: see Section 4). It is not obvious that this was a particularly wise thing to do (even though it had the Royal Society's imprimatur) since it created an illusion of invulnerability and consequent progressive enlightenment amongst earthlings, a condition which is liable now to be rather too rudely awakened by a potential catastrophe and not necessarily in sufficient time to handle successfully a rapidly developing course of events. It would not be an exaggeration to attribute this kind of illusion (in an extreme form) to western civilization today. In fact, this tendency of astronomers and cosmologists to stumble somewhat clumsily towards a unified understanding of our environment has frequently been noticed. After all the Greek Aristarchus seriously adopted the heliocentric viewpoint some 18 centuries before Copernicus and it is well known that one reviewer in modern times (Koestler 1959) was

so incensed as to conclude that he was dealing with a profession of "sleepwalkers". More politely perhaps, one may recognize a type of inertia in the body astronomic which can be conveniently evaded as such by use of the term "paradigm" (Kuhn 1962).

The paradigm shift to which we refer, then, is restoration of the Platonist viewpoint. Plato, it is now clear was aware of the great Bronze Age destructions known to us through archaeological research. Such catastrophes due supposedly to random celestial bombardments were evidently thought of as part and parcel of an intermittently active celestial environment which also included periodic, major inundations of celestial debris such as are now associated with the core of the so-called "Encke-Taurid" stream in sub-Jovian space (Asher & Clube 1993). These inundations towards the end of the 3rd millenium BC (2200 - 2000BC) and the middle of the 1st millenium BC (400 - 600AD), coinciding with the demise of two great civilizations of the past (the Sumerians and the Romans), are perhaps among the most striking in history but there are many other relatively sudden collapses of civilizations (eg the Myceneans, the Minoans, the Hittites, the Sixth Egyptian Dynasty, the Classical Maya, the Chinese "Warring States", the Indus Valley etc) at other epochs which remain to be tested as examples of the kind of celestial pressure which we are now considering. Plato however, it is now clear, was also the voice of reason behind a fundamentalist, apocalyptic tradition over which governments were frequently unable to exercise control (eg Heinsohn 1995, Clube 1996). Indeed, the neo - Platonists, the early Christians, the Islamic movement and many others all gained long-lasting strength whilst challenging the demonstrable failings of an enforced Aristotelian cosmos designed merely "to save appearances". In spite of this, the Christian, Islamic and Judaic cultures have all moved since the European Renaissance to adopt an unreasoning anti-apocalyptic stance, apparently unaware of the burgeoning science of catastrophes. History, it now seems, is repeating itself: it has taken the Space Age to revive the Platonist voice of reason but it emerges this time within a modern anti-fundamentalist, anti-apocalyptic tradition over which governments may, as before, be unable to exercise control. The logical response is perhaps a commitment on the part of government to the voice of reason (cf Sections 4 - 8 below) and a decision to eliminate all signs as well as perpetrators of cosmic catastrophes (ie all bodies > 10 metres approaching the Earth) in order to appease a public now too far given to rabid uniformitarianism. ***Cynics (or modern sophists), in other words, would say that we do not need the celestial threat to disguise Cold War intentions; rather we need the Cold War to disguise celestial intentions!***

4. Giant Comets

For most of the present century asteroids have been regarded as distinct from comets in appearance, composition and provenance. This traditional distinction continues, and the assumption that Earth-crossers are rocky or metallic strays from the main belt is often implicit in discussions of the impact hazard (e.g. Chapman & Morrison 1994). This assumption leads to a risk assessment which, in nature and timescale, is altogether different from that we are now considering here. Thus, in recent years, the division between comets and asteroids has become increasingly archaic. The absence of gas and dust emissions is no longer a secure guide to the nature of an asteroidal body. Several comets have, in recent returns, been asteroidal in appearance while there are now over 50 (from 200) asteroids, defined by appearance, which are 'comets' as defined by orbit. Meteor evidence leads to the same conclusion; thus many fireballs of cometary constitution are found to have 'Apollo asteroid' orbits, and meteoroid streams appear to be associated with every known Apollo (Earth-crossing) asteroid which approaches within 0.1AU of the Earth.

An important finding is that about a dozen of the known Earth-crossers >1 km across are co-orbiting with Comet 2P/Encke and appear to be degassed remnants of an erstwhile giant short-period comet (P~3.3 yr) thrown into the inner planetary system. In total, in this region, there may be about 100 (out of 2000) such asteroids, and it appears that Comet Encke, the co-orbiting asteroids and the associated Taurid meteor streams form a conspicuous Complex (~ 50% of interplanetary mass) derived from the break-up of this erstwhile Earth-crossing giant comet (Asher et al. 1994, Asher & Clube 1993). It now seems probable, therefore, that a significant fraction of the Earth-crossing asteroids are in fact dormant comets and that some of these may be trapped into Jovian orbits (like Shoemaker-Levy) from time to time. But while the giant comet may be erstwhile its fragmentation debris are not. They are ostensibly the prime source of the inner Solar System dust. Indeed the orbital spread of the debris clearly points to a physical connection with the last major glaciation at the end of the Pleistocene (ca 30,000-10,000 BP). And it is the giant comet/major glaciation connection which now provides us with the key that unlocks the various periodicities in the more extended terrestrial record. Bouts of global warming (including the present one) for example during the Holocene at 2,500 yr intervals (Kerr 1996, O'Brien et al 1995) clearly connect with the proto-Encke

core of the Taurids while the 100,000 yr glacial cycle since ~1,000,000 BP, coinciding with the Sun's current Galactic plane crossing, may signify a dynamical corridor which opens up between the Oort cloud (under Galactic control) and the inner Solar System at regular (deterministic) intervals.

Giant comets both strongly dominate the mass influx to the near-Earth system and yield a highly variable mass input. The mass influx is long-term periodic (see later) indicating the flux of long-period comets into the Solar System is its primary source. Best estimates yield a cumulative flux of long-period comets, at the high mass end, given by

$$F \sim 1 \times (d/5)^{-2}$$

comets AU^{-1} yr^{-1}, d the diameter of the comet in km (Bailey et al. 1994). There is no securely known upper limit to d, but several historical comets appear to have been >100-500 km in diameter. A giant long-period comet (>100 km) is therefore expected to cross the Earth's orbit about once every 400 yr, a Chiron-sized body (~300 km) once within the time scale of civilization. The injection rate of giant comets from a chaotic, trans-Saturnian orbit into a stable Earth-crossing one is of order 10 Myr^{-1} (loc. cit), that is at much the same rate as that at which kilometre-plus asteroids strike the Earth. In the discussion following we neglect the relatively minor main belt asteroid component and concentrate on the dominant mass influx, due to disintegrating giant comets. It has recently been assumed (e.g. Chapman & Morrison 1994, Brandt & Chapman 1982) that the current terrestrial input rate be derived from the small crater count on the lunar maria. However, these counts have a time resolution ~3300 Myr, the ages of the maria, whereas the mass influx is highly variable on timescales <0.1 Myr. Thus, in attempting to estimate the current impact rate on the Earth, the lunar crater counts are of little value. A more reliable (but still very imperfect) guide to contemporary rates is provided by the cometary:meteoritic excess ~$10\text{-}10^2$ in the impactor range <10m observed in the zodiacal dust input and kiloton-to-megaton fireballs. Lacking an inventory of the near-Earth population, one must hang these very limited observational data on to a model representing the near-Earth flux and their observed splitting rate.

'Spontaneous' disintegration of comets is a common phenomenon and may lead to a temporary excess of cometary over meteoritic (i.e. main belt asteroidal) material by a factor ~ 100 - 10,000 in the impactor range up to a few km diameter. Such disintegration is generally expected to proceed via short-lived 'asteroids' (~30,000 yr) of cometary

provenance, many of which remain in near-progenitor orbits whilst others may deviate more widely into an extensive meteoroidal complex. Small (Tunguska-sized) bodies, deriving from such heirarchic breakup, will tend to spread out along individual orbits over ~ 200yr, but will also result in a fairly concentrated core-stream if a significant progenitor remnant survives, even bunching in mean anomaly if they inhabit a mean-motion resonance with Jupiter. Nodal intersections with individual deviant orbits and with core-streams will both occur quasi-periodically on timescales 100-10,000 yr. Alternatively, in cases where the heirarchic breakup is itself catastrophic (i.e. due to impacts on relatively fragile asteroids) and the disintegration products are rather more widely dispersed, we anticipate a bombardment on a shorter timescale (say ~ 20 yr) due to a relatively broader stream.

As already mentioned, several lines of evidence indicate that the Earth is currently interacting with the remnants of an erstwhile giant comet in a short-period orbit. Thus there may be ~ 100 asteroids co-orbiting within the Taurid meteor stream and 2P/Encke, themselves immersed in the much broader Stohl streams which merge into the Zodiacal Cloud (Asher et al. 1994). This 'Taurid Complex' has been directly detected by the recent LDEF satellite experiment and also dominates the radar meteor flux (Steel 1996). The debris still presents a 'Tunguska' and 'super-Tunguska' hazard to mankind both globally (integrated destructive power ~ 10,000 Mt; hazard duration ~ 200 yr; and interval ~ 2,500 yr) and locally (integrated rates destructive power ~ 10-1000 Mt; hazard duration ~ 20-100 yr; and interval ~ 250 yr). These are also consistent with the extreme surges in Taurid bright fireball flux which have occurred over the last two millennia, the intervals being significantly shorter than those associated with the impacts of >1km asteroids (~100,000 yr). ***All in all, it now seems very unlikely that past generations were unaware of this distinctive cometary hazard. It behoves us to examine how the crises were handled in the past and to consider how they might be met in the future.***

5. Climatic response

A Chiron-sized body undergoing disintegration in a short-period orbit will generate say ~ 5 $\times 10^{21}$g of dust over a ~3,000 yr active period, assuming a dust-to-gas ratio of say 3:1 and a disintegration history as described by Kresak & Kresakova (1975). Over timescales ~0.1 Myr, the micron-sized dust population may then fluctuate by three or four powers of ten, dominated by the input from the most massive comets. A giant comet

disintegration will thus result in prolonged stratospheric dusting (~1000-10,000yr), the dust veil having optical depth $0.05<\tau<3.0$, say and the Earth will then be enveloped in a highly reflective dust cloud. Such dusting is not an ad hoc proposal but is an expectation deriving from the nature of the interplanetary environment. We summarise the expectations based on this input and consider these in relation to some of the evidence.

5.1 Expectations: To judge likely terrestrial effects, limited comparisons may be made with nuclear winter studies. The earliest nuclear winter models (Turco et al. 1983: TTAPS hereinafter) were one-dimensional, assuming a hemispheric distribution of smoke and dust, and neglecting feedback effects from cryosphere and oceans. Typically in such runs the initial optical depth is $\tau \sim 4$, of which $\tau \sim 3$ is due to smoke injected into the stratosphere, while fine dust (<10μm radius) reaching the stratosphere has $\tau \sim 1$. The overall optical depth declines to $\tau \sim 2$ after three months. In these models temperature drops $\Delta T \sim 40°C$ are reached ~ 20 days after the dust injection, with recovery times of over a year. Second generation models incorporated snow and ice feedback, and took account of the thermal inertia of the oceans, which moderated the land temperature response Robock (1984) assumed the injection of smoke in a uniform latitude band between 30° and 70° N, and distributed between 1 and 10 km in altitude. Incorporating seasonal crysospheric interactions he found that land temperatures were ~ 6°C colder than normal in the second year after smoke injection. Covey et al. (1987) modelled variations in sea ice and sea surface temperature, and found that maximum northern hemisphere cooling after 20 days were typically ~ 25°C in July, ~ 15° C in April and ~ 5° C in January; thus the ocean moderates a cooling by a factor of about two. A third generation of models (e.g. Schneider & Thompson 1987) has moderated these predictions by a further factor of two, yielding $\Delta T \sim$ 10°C for the baseline July case. This results from the incorporation of two additional factors: (i) the infrared opacity of the smoke allows for a compensatory 'greenhouse effect'; and (ii) the smoke distribution is patchy, allows sunlight to penetrate from time to time. Thus these models point to a 'nuclear autumn' rather than a 'nuclear winter'.

However, there are indications that a 'cosmic winter' might be considerably more severe than a nuclear autumn, since the 'third generation' factors do not apply to the acute climatic effects of cometary dusting. Thus whereas in the nuclear winter scenarios tropospheric dust is the predominant absorber of sunlight, and is removed in some weeks, in the 'cosmic winter' situation tropospheric dust is relatively unimportant, the scattering of sunlight being due to sub-μm Brownlee particles in the stratosphere, with a residence time

of a year or more. Further, the patchiness simulated in the later models does not occur with cometary dusting. Additionally, dust injection from high level disintegrations is global rather than hemispheric, and there is no moderation of climatic severity from warm ocean currents entering from the southern to northern hemispheres. Thus at the qualitative level it appears that the prompt effects of a cosmic winter are more closely simulated by the first or second generation 'nuclear winter' models rather than by later 'nuclear fall' ones.

The likely biological effects of a TTAPS-type nuclear winter have been examined by a number of authors (e.g. Ehrlich et al. 1983). Exposure to a temperature drop of only a few degrees, for even a few days, during the growth season, is sufficient to destroy many crops, while a temperature drop >30°C in the growing season (July in the northern hemiphere) is more than adequate to bring commercial agriculture to an end. Other relevant factors (Ehrlich et al. 1983) include the disruption of man-made energy subsidies necessary for the major crops and the effect of reduced continental precipation. Since crop productivity is linearly proportional to the degree of exposure to sunlight, many plants would disappear by virtue of reduced light alone. Tropical terrestrial ecosystems are less adapted to prolonged darkness or cold, and Ehrlich et al. (1983) consider that most forests and terrestrial species would disappear. They consider that 'the possibility of the extinction of Homo sapiens cannot be excluded'. These effects are acute rather than chronic; however the latter are likely to have the most far-reaching consequences in biological terms. Unfortunately the chronic effects are dependent on ill-understood feedbacks and have hardly been modelled. A decline of 5-40% in solar insolation for a year or more, which is within the parameter range under discussion, might cause a drastic reduction in monsoon rainfall, with a catastrophic effect on much of the world's agriculture (Barnett et al. 1988).

5.2 Evidence: Within the last year or two geochemical evidence has begun to emerge which appears to link climatic perturbations to celestial disturbance on virtually all timescales

(i) Centennial.

The dust imput described above derives from prompt meteoric and meteoroidal input, many larger bodies disintegrating during pre-atmospheric entry and atmospheric descent to ~ μm-sized dust particles. Significant prompt injection of dust from the impact of much larger (super-Tunguska) bodies is also expected, at characteristic intervals of some

centuries. The dust veils from such events may be initially hemispheric, but could still yield measurable climatic and agricultural effects over some years. The dust-veil of AD 536 ($\tau \sim 2.5$) might be of this character as it appears not to be associated with a volcanic acidity signal. A causal relationship has been proposed between this dust veil and the severe cold and famine at this time, the latter documented throughout the Old World and presaging the arrival of the Justinian Plague (Baillie1994).

(ii) Millennial.

Both the AD 536 event and the 17th century Little Ice Age are correlated with known surges in the Taurid meteorid flux, believed also to be the likely source of the Tunguska object in 1908. Indeed a specific dynamical model for the largest surviving remnant of the Taurid progenitor based on observations of Comet Encke and Taurid meteoroids (Asher & Clube 1993) predicts major bombardments of the Earth, and associated global cooling, for several centuries circa AD 500 ± 2500n , n=0,1,2,... as our planet encounters the precessing nodes of the progenitor orbit. A climatic oscillation of this period *and* phase has been inferred from the deposits of ice-rafted debris which are now detected in ocean sediment cores, reaching through the Holocene and beyond (see Section 4).

(iii) Quaternary

It has recently been found that ^{3}He (a comet dust marker) was laid down with a 100 kyr cycle during the Quaternary (Farley & Patterson 1995), the deposition correlating closely with the known climatic oscillation of this period.

(iv) Cenozoic.

On the longer Cenozoic timescale, strong surges of ^{3}He occur in association with tektites and mass extinction horizons, providing 'strong evidence for multiple terrestrial impact events associated with dust-bearing objects...' (Farley 1995). These variations and correlations were predicted (Clube & Napier 1984, 1986) and appear also to show the expected Galactic periodicity of ~ 26 Myr during the Phanerozoic (Rampino 1994, Clube & Napier 1996).

The table below summarises the characteristic timescales associated with the various hazards to civilization identified in this report from the near-Earth environment. Figures are intended only as a very crude guide.

TABLE I

Nature of hazard	integrated impact energy (Mt)	duration of trauma (yr)	recurrence time
stray Tunguska	10-100	1-10	250
Tunguska swarm	1,000	20	250
super-Tunguska swarm	10,000	20-200	2500
giant comet dusting		3,000-30,000	10,000-100,000
1 km asteroid	100,000	1-10	100,000

6. Human response

That astronomy developed purely from calendrical and navigational requirements is a common misconception. Thus, in parallel with civilization itself, astronomy developed from the practical and theoretical needs of "omen astrology" during the long decline of the Sumerian empire (ending ca 2000 BC), to be matched approximately 2500 years later by the decline of the Roman empire (ending ca 500 AD, cf item 5.2 (ii)). But whereas the classical period resorted to somewhat mystical practices of divination etc. in order to anticipate and allay the doom-laden future, the cradle of civilization's state-astronomers were altogether more earnest and relied upon their network of sky-watchers stationed in towns and villages to report the incidence of fireballs, though likewise to no avail! This robustly practical approach to the celestial threat was subsequently continued in China into early modern times - their astronomical records are now invaluable - but has emerged only intermittently in the West. One notes for example that "towards the end of Cromwellian Protectorate an even more elaborate design for registering illustrious providences (i.e. fireballs) was initiated ... the close parallel with the methods of the scientists of the Royal Society for collecting and classifying natural phenomena is obvious enough" (Thomas 1971). Such plans in England are attributed to a presbyterian minister, one Matthew Poole, who envisaged that every county should have a secretary who would gather together the material sent to him and forward it to Syon College for analysis. Francis Bacon indeed had previously urged the desirability of compiling a definitive history of the working of providence and one Increase Mather matched these plans in New England with

his Boston publication in 1684, an *Essay for the Recording of Illustrious Providences,* which drew upon a manuscript left by Poole. Three centuries later, the Space Age and modern technology have brought us once again to the equivalent position in the West - already we are past the half-way mark from the last Dark Age (see Section 5.2 (ii)) and the countdown to the next (ca 3000 AD) has begun!

7. Future investigations.

With the completion of this project, the broad features of the giant comet threat have been laid bare. The immediate requirement now is to examine the detailed effects of giant comet disintegration from the perspectives of astronomy, climatology and history. This is virtually unexplored territory, but has the potential to yield significant new understanding in the fields of both human and Earth history, including a more realistic perception of the current celestial hazard. Such a project may serve both as the basis for reappraisal of putative 'spaceguard'-type search programmes and as the foundation for a wider public discussion.

7.1 Matters arising in Astronomy.

The finding that comet dust input (as measured by ^{3}He deposition) is highly variable on geological timescales, with a Galactic periodicity, suggests that the Oort Cloud (which reaches half way to the nearest stars) rather than the Kuiper Belt (which merely encircles the planetary system) is the ultimate source of the Earth-crossing comets (and cometary asteroids) which deposit material on the Earth. Indeed, the emphasis on giant comets leads us now to recognize the Inner Oort Cloud as the primary source of comets deflected into the planetary system whence such objects undergoing a wide variety of weak transitions (including mean-motion and secular resonances) from one orbital energy state to another are transferred either back to the Oort Cloud, into longer lasting Kuiper Belt orbits or into sub-Jovian, near-Earth space where they are rapidly destroyed. The dynamical highways connecting Oort cloud to inner planetary system are still somewhat unexplored. However the disintegration of a very large comet during a single passage within the Roche lobe of Jupiter could in principle replenish the entire Jupiter comet family. Thus the interplanetary small-body population, including Earth-crossers, is likely to be highly variable on relatively short timescales, as indeed the ^{3}He deposition record implies.

A Markov chain approach may be used to examine this process. Transition probabilities between various interplanetary orbital states (Halley-type, Jupiter-type, Encke-type, Saturn-crossing etc.) have been found by several workers in recent years, and these may be used as the elements of a transition matrix. Monte Carlo simulations using the chain may then enable the fluctuating nature of the very short-period system to be studied in a quantitative fashion. The foundation will thus be in place for a variety of Solar System periodicities naturally arising in association with the Galaxy, Oort cloud and planetary system interactions ranging from 26/13 Myr at one end of the scale and 2500 yr at the other. A three-dimensional, time-varying model of the zodiacal dust distribution may then be constructed with the above disintegrating comet population as the dust source. This problem is very complex since the grains will be subject to mutual collisions, gravitational scattering by the planets and trapping into mean motion resonances, in addition to radiation pressure and Poynting-Robertson effects. Grain segregation by chemical type may also occur and could manifest itself in the geochemical record (Wickramasinghe & Wallis 1994). This part of the project is likely to be computationally intensive: Jackson & Zook (1992) quote an hour of Cray X-MP cpu time as necessary to follow the evolution of a single dust particle for 200,000 years, using the Everhart integrator (given the high particle collision rates expected during a giant comet disintegration, symplectic techniques will probably not prove suitable).

A statistical analysis of the orbits of the known Earth-crossers may also be envisaged, to search for 'fossil evidence' of erstwhile giant comets in the form of significantly close orbits (cf the Taurid Complex asteroids). Preliminary evidence for such orbital bunching already exists (Napier 1996). This statistical analysis in conjunction with the growing catalogue of objects in Earth-crossing orbits would provide more information about the structure of the near-Earth population, with which the more immediate fireball data (for example recently declassified USAF satellite information) might be correlated.

7.2 Matters arising in Climatology.

Events of the "Justinian variety" might be ascribed to 'prompt' dust injection, of order a year, following a Tunguska-like impact. However the period of severe cooling following impact, Plinian eruption or nuclear war is too short to overcome the thermal inertia of the oceans, which have a cooling time of perhaps a decade. Thus such brief coolings, although severe, are probably reversible. This suggests the greatest danger are associated with super-Tunguska inputs which disintegrate during pre-atmospheric entry,

the comminution continuing to the level of sub-micron dust. Such material remains in the atmosphere over more extended timescales. Moreover, when the insolation is significantly lowered for a timescale of the oceanic cooling time, the ocean can no longer act as a buffer. Water vapour transport from the oceans to the >20 μm photosphere is cooled to below -50° C, a haze of atmospheric ice crystals forms increasing the albedo by ~ 0.3 and reducing the mean ground temperature to ~280° K. The latter corresponds to ice age conditions. Thus prolonged cometary dusting might rapidly trigger a runaway glaciation, consistent with observed 'Taurid' remains of a giant short-period comet which may well have been much more active during the last one (Hoyle 1981; Clube, Hoyle, Napier & Wickramasinghe, 1996).

This 'ice haze' formation process may be simulated using zonally-averaged energy balance models with one-dimensional radiative-convective transfer (Caldeira & Kasting 1992). Since the essence of the mechanism is a reduced insolation for a time in excess of the oceanic cooling time, additional feedbacks may have to be incorporated. Both low-level and severe effects need to be considered; the former may provide an insight into the recently discovered correlation between comet dust input and the 100,000 year climatic cycle; the latter is necessary to assess the probability that giant comet dusting would plunge the Earth into an ice age. The latter would of course represent a catastrophe of great intensity, in which a substantial decline in the human population is expected, possibly coupled with a reversal of civilization, even to the point of mere subsistence survival over most of the globe.

7.3 Matters arising in History.

The working model which relates to the Taurid progenitor and its disintegration debris during the Holocene now provides a relatively secure basis for evaluating the socio-political consequences of predicted celestial inputs (at intervals > 10^2 yr) which are evidently perceived as both drastic and highly probable. In fact the historical record apparently indicates a regular divergence of views on such occasions in that mankind reacts by drawing upon extreme reserves of stoicism and hedonism in more or less equal measure. Under normal circumstances mankind merely draws upon these reserves to a modest extent unrelated to the state of the interplanetary environment - indeed mankind cultivates a disdain for such predictions even to the extent of being unaware that the hazard exists!

Since stoicism is more or less an absolute requirement for large scale human survival in the aftermath of catastrophes such as ice ages (ie on timescales > 10^5 yr say), this situation creates something of a dilemma for civilization on timescales ~ 10^2-10^5yr. The dilemma seems to materialise in the form of a revived eschatological debate (ie concern over the perceived impending end of the world) under circumstances (globally) which are commonly associated with 'state crises'. Indeed, if the cyclic view of history is re-established, as it was accepted before the Enlightenment, and there is (as the giant comet evolutionary picture suggests) an overriding natural mechanism beyond warfare which forces nation states to destabilize and subsequently revive, more or less in unison, then civilization is commonly subjected to a serious socio-political imbalance which is currently more or less unrecognized.

Indeed, it apparently turns out that ordered societies on the scale of nation states are particularly vulnerable to complete breakdown when the circumstances are such that **all levels** of society react simultaneously to a crisis in the same way (as above) and when the course of events (e.g. demographic change due to widespread infection, climate change etc.) acts non-linearly on marginal groups within the populations at stake. Recent studies (eg. Goldstone loc cit.) have concentrated on the correlated breakdowns during the mid-seventeenth, late eighteenth and mid-nineteenth centuries for which the case studies (English Civil War, French Revolution etc.) are most complete. Significantly, each of these correlations is associated with an extreme bombardment by cometary debris (Clube 1996) and a reconstruction of the celestial past on the basis of the historical and proto-historical record may now be seriously contemplated (cf Clube & Napier 1990, Cohn 1993, Hoyle 1993). The future implications for government and society as a whole are profound and the investigations so far have done little more than set the scene in sufficient detail for a multiplicity of derivative investigations.

8. Conclusion and reflection.

The reader of this report will be conscious of an unusual interplay between science and history. From some of those who have already engaged with the relevant knowledge, there is frequently an overt demand that new interpretations of old facts are not confronted "head on" out of concern for some affectation or belief on the part of the reader. The hinterland between history and science is in fact an intellectual minefield and

it is customary for historians and scientists to limit communication across the eschatological-astrological divide. The demands for care at this divide can of course be reasonable but there is also a point where the contortions of language necessary to comply with the varied niceties of thought which arise from fundamentally incorrect premisses may not be fruitful. After all, we already belong to an age so fully committed to its (politically correct) uniformitarian outlook that those who assume authority over it seem automatically to suppose that any perceived defects of the environment (eg global warming, ozone depletion) can only be due to mankind and controlled accordingly. The idea that *natural* catastrophes may have to be confronted is unquestionably remote. Under these circumstances, any upset occasioned by a seemingly confrontational approach in relation to the subject matter of this report is presumably a small price to pay when the enterprise at stake can affect the condition of mankind and civilization itself. Needless to say, it is assumed by the author that cometary science is a serious business and does indeed extend to matters affecting the well being and survival of mankind.

Under these circumstances, then, one has to reflect why it is that the Space Age arm of the most powerful civilization in the world voluntarily jettisoned its 1970's opportunity to plan a 1986 rendezvous in space with Comet Halley. Thus it is an indisputable fact that ESA not NASA took the plaudits for Giotto, betokening a serious cultural bias against comets in the US (apparent also in the UK) during the 1960s and 1970s. This bias, though now reduced, is still evident in the justification for Spaceguard and can, to a degree, be extended to the US scientific leadership generally.

Like many other astrophysicists, the present author was not immune to this bias. However it was his privilege to have Sir Richard Woolley (Astronomer Royal), of "space is bunk" renown, as his prime mentor; and it was not possible with this background other than to reflect on the cultural conditions which inspired such celestial contempt coupled with astrophysical foresight. The point here is that the inferred correlations between the cratering flux and near-Earth asteroids first arose during the 1960s and 1970s; and although this knowledge was pioneered and first clearly recognised by (cometary) astronomers (eg Fred Whipple in the US and Ernst Opik in the UK), it was chiefly a catastrophist geologist (Eugene Shoemaker) in the United States, during this period of extreme astrophysical bias, who first assembled critical evidence and unwittingly influenced an orientation of the subject towards geological time-scales (10^5 - $10^{9.7}$ years). The shorter timescales (< 10^5 years), uniquely associated with giant comets, were unfortunately neglected - especially in the United States.

By now, of course, the cultural bias against comets, so long sustained by uniformitarian astrophysicists and geologists as well as by society as a whole, is in decline. The meetings at San Juan Capistrano, Tucson and Erice have served the purpose of bringing in contact some of those engaged in the relevant research. Fate itself determined that a catastrophist geologist was not around for a geological timescale before witnessing an astronomical catastrophe! Now there is a prospect also of the more integrated view of our celestial environment promoted in this report being recognized further afield: the outcome, for sure, will be a realization that the hazard from space has something like a 1 in 3 lifetime chance of recurring - essentially outstripping the individual probabilities publicized by the Spaceguard Report. The modern strategy for dealing with this situation is not yet in place.

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