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Risks in space

ARNOLD WOLFENDALE

Department of Physics, University of Durham, Durham DH1 3LE, UK.
E-mail: A.W.Wolfendale@durham.ac.uk

The human species is beset by 'risks'; one of which is related to its exposed position on the Earth as it travels through cosmic space. An examination is made of the major risks – those associated with cometary impact, with solar emissions and with the explosions of nearby stars. Estimates are given of the risks associated with trying to avoid the effect of these phenomena. Not surprisingly it is concluded that more work is necessary.

Introduction

Concerning my title, the Professor on the British wartime 'Brains Trust' (C. E. M. Joad) would have said, 'it all depends on what you mean by risk' and by 'space'! Here, by 'risk', I refer to the hazard to mankind, either catastrophic or otherwise, and by 'space' I mean extraterrestrial space – that region of the universe through which the earth is passing on its (hopefully) long journey.

The risks are manifold, but special mention will be made of the effect of the impact of asteroids and comets, the Sun, so-called cosmic radiation, and the threat from nearby exploding stars.

When one looks at the threats posed by these phenomena it makes one think that we are lucky to be here at all. In fact, it may well be that we're here *because* of some of them. But 'he who givest, takest away …' so future effects may not be at all beneficial, at least in the short term.

Quantification of the various risks will be attempted and attention will be given to the public perception of these risks.

Comets and asteroids

General remarks

The distinction between comets and asteroids is described in Table 1. Together with meteorites they are called 'bolides', but here we often refer to them all as comets. Starting with the largest bolides – epitomized by the great comet of some

Table 1. Comets and Asteroids: the differences

- Comets are generally bigger and they come from further away. Many are dirty snowballs and the material 'evaporated' by sunlight gives them their characteristic tails when close to the Sun.
- Asteroids come mainly from the region between Mars and Jupiter. Many are composed of carbon-containing material, of rocks or of metal. Their velocities on arrival are lower but their number in the vicinity of the solar system makes the risk of their colliding some four times as great as that of comets.
- Asteroids are invariably very dark and, in consequence, difficult to detect until they are very close!

65 million years ago that fell on the Mexican coast and almost certainly wiped out the dinosaurs – the hazard comes from the material thrown into the atmosphere after the impact. This material blots out the sunlight over, perhaps, the whole globe, with the consequent destruction of species. Giant ocean waves (tsunamis) will also create great damage when comets fall in the sea. At the other extreme, the earth is continuously being bombarded by dust from fragmented comets (micrometeorites etc) and this dust can have important climactic effects. The time variability of the arrival of this material has fascinating potential relevance to Global Warming, a fact only recently appreciated.[1]

Historical aspects

It is commonly asserted that the ancients feared comets because they were harbingers of doom – the implication being that it was all a case of superstition. In fact, it seems that the situation is more complicated than that, as has been well brought out in an article by Bailey *et al.*[2] Their arguments are relevant to the present consideration of future risks from cometary impacts, and not just from the (nevertheless important) aspect of historical appreciation. The authors argue that, although astrology per se is nonsense, some aspects may – almost unbelievably – be based on fact. It seems that the Babylonians had quite advanced views about comets and meteors, notwithstanding their tendency to name them after gods. They became convinced about their relevance to terrestrial events; specifically, the fall of iron meteorites and, perhaps, some minor climate changes. Ideas about the relevance of astronomical events to earthly affairs were continued by later races, although without the associated evidence; for example, Bede (AD 673–735) maintained that comets were precursors of disasters, and even as late as the 16th century, the Chinese emperors had astrologers to foretell the future based on astronomical happenings. An interesting example of the observation of a comet,

Figure 1. Halley's comet in AD 1066 as viewed with trepidation by King Harold's court. The picture is from the Bayeux tapestry. The caption reads *isti mirant stella*, 'They wonder at the star'.

and the obvious terror of the observers, is afforded by the picture of Halley's comet (Figure 1) in the Bayeux tapestry. The comet appeared in England in 1066 and was seen by King Harold and his court. The least distance from the earth was only 16 million km.

The portent-of-disaster attitude has been pooh-poohed by the more recent scientific fraternity, and rightly so, from the standpoint of astrology per se being quite mad. However, the point made by Bailey *et al.*[2] is that, in the Babylonian period, when the ideas started, there is some evidence for there having been greater meteoritic and cometary activity than more recently. The higher rate of impact of meteorites on the Earth and the visible drama of comparatively frequent comet sightings would, understandably, heighten fears about celestial events.

All the above is not to imply that the author believes in any aspect of astrology. The effect of planetary conjunctions and so on having an effect on humans is nonsense, the point is simply that the aspect of astrology related to a fear of comets and meteorites may have a sensible origin.

Cometary rates

Table 2 gives what might be called 'conservative' rates for the impact of comets and asteroids on the Earth. It is conventional (nowadays) to give the equivalent number of megatons of TNT, as shown, and this is given as a function

Table 2. Impact of comets and asteroids (near earth objects, NEOs) on the earth

NEO diameter	Yield (megatons)	Average interval between impacts (years)	Crater diameter per impact	Average fatalities
75 m	10–100	1000	1.5 km	10 000
350 m	1000–10 000	16 000	6 km	300 000
1.7 km	0.1–1 mill.	250 000	30	1.5 billion
7 km	10–100 mill.	10 mill.	125	6 billion
16 km	0.1–1 bill.	100 mill.	250	6 billion

of the diameter of the body. Also given in the table is the diameter of the crater and, importantly from the point of view of 'risk', the average time interval between impacts.

A brief commentary can be given about the table. The famous air burst at Tunguska in Siberia in 1908 was caused by a 'small' object (probably a stony asteroid) of about 50 m in diameter. It flattened some 2000 km^2 of forest and, had it struck a well-populated area, the death toll would have been considerable. The well-known Barringer crater (Figure 2) was produced by an iron asteroid of similar size. Very recently, in June 2002, a somewhat larger asteroid is reputed to have missed the Earth by less than ten Earth radii.

At the one-per-250 000 year level, the bolide diameter is about 1.7 km and the effect of the impact would be very great. A land impact would cause climate change by way of ozone destruction and dust generation. An ocean impact would cause vast water displacements (tsunamis) and great loss of life in coastal areas. At the 16 km diameter level, the size of Halley's comet, and of the comet responsible for the death of the dinosaurs, one expects virtually all the earth's population to be wiped out.

The risk

In one sense, the risk is bound up with the product of the average number of fatalities per impact and the probability of an impact (say, per year). Inspection of Figure 3 shows that, up to intervals of about 30 000 years, the result indicates about ten fatalities per year. Above this, however, there is a dramatic increase to about 10 000 per year, falling back to about ten per year by 10^9 years. It must be borne in mind that these numbers are very approximate; they are also averages for frequency distributions that are very wide indeed. As remarked earlier, a Tunguska-sized asteroid falling on a densely populated area would cause very many fatalities, but in a desert there would almost certainly be none.

Figure 2. The Barringer crater in Arizona. The 1.2 km diameter crater was created 49 000 years ago, a small nickel-iron asteroid being responsible. Objects this size are expected to hit the earth somewhere about every thousand years.

The peak probability in Figure 3 is $1.5 \times 10^9/10^5$/year, i.e. 15 000 fatalities per year, worldwide. Converting this to the UK, as an example, would probably give a mean value of about 200 per year. In fact, this could be a considerable underestimate if, following the arguments advanced in the first section, there is variability in the mean rate and we are, perhaps, in a period of low rate at present.

Even with a rate of 200 per year, the risk is clearly not negligible. Of course, 200 fatalities each and every year would cause a great outcry and certain 'action'. The actual situation with most years free and only the very, very rare drama of many thousands of casualties, is still a cause for concern. UK safety standards are such that protection measures against floods, nuclear power plant accidents or nuclear waste leaks, all consider that such rare risks are worthy of assessment and precautionary action.

Public perceptions of the risk

Public attitudes to comet and asteroid impacts and their risks have been, on the whole, remarkably laid back. Whilst comparable – or smaller – risks associated with 'mad cow disease', Chernobyl-type disasters and the like are given

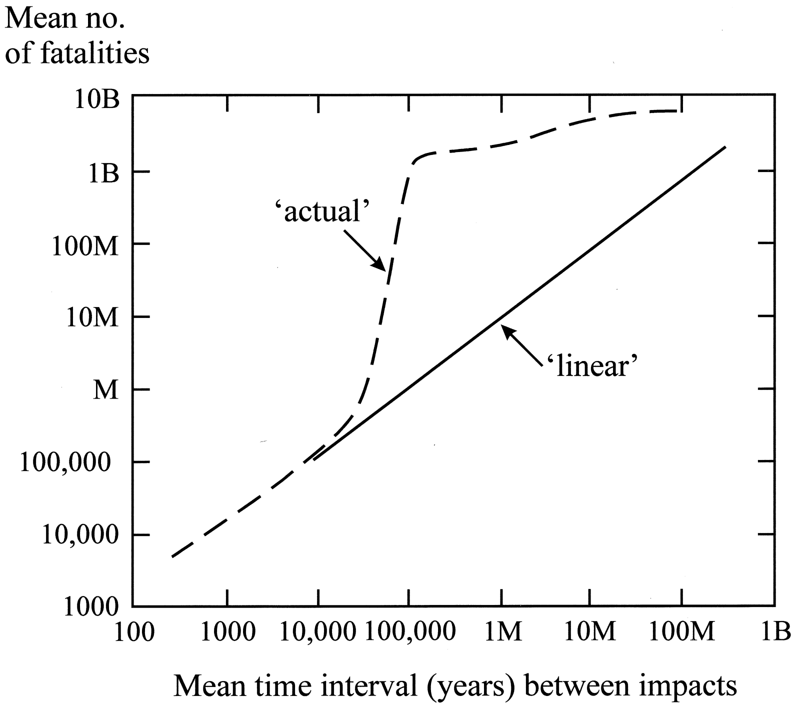

Figure 3. Average number of fatalities per impact versus the mean time interval between impacts. 'Report of the Task Force on potentially hazardous Near-Earth Objects', 2000[4] (M = million, B = billion). There will be a large spread in actual values from one impact to another but the mean is probably accurate to within a factor 3.

near-hysterical treatment by the media, cometary impacts appear to be ignored, except by a few. At first sight, the recent report[4] by a committee set up by the UK Government to study 'potentially hazardous Near Earth Objects' seems to be praiseworthy, but the 'proof of the pudding is in the funding' and the funds allocated for necessary further studies have been derisory. The attitude of politicians to cosmic phenomena, life-threatening as they may be with comets or in a search for extraterrestrial life, is a fascinating one in its own right and worthy of study – but not here.

Why are most of the public so blasé? In addition to the media's lack of interest, perhaps history (see the first section) gives a clue. Post-Aristotle, the view of a rather mechanistic earth-centred perfect solar system, with the earth at its centre was *de rigueur.* This, coupled with the Christian view that all was perfect in the Universe with the exception of humans, and they would be saved by a manifestation of the deity, left no room for extra-terrestrial life terminators. It is true that, post-Copernicus and Galileo, realization of the Sun's pre-eminence, and

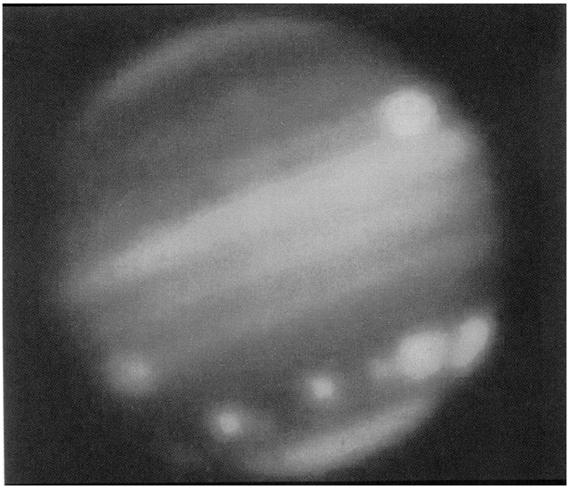

Figure 4. A view of the planet Jupiter on 21 July 1994. The comet Shoemaker–Levy 9 broke into a series of fragments before impact and they produced the series of bright spots (each the size of the Earth) near the bottom of the planet. The bright spot top right is Io, one of Jupiter's satellites and a fascinating object in its own right.

its lack of perfection, appeared; but serious attention to a quantification of the risk of cometary collisions has been very rare.

No doubt the dismissal of astrology by most people, despite an amused fascination with horoscopes, has played a large part, at least until very recently. Now, perhaps, the public is starting to be interested. One reason is the fascination with all things astronomical, and particularly those cosmological. In turn, some would say that 'cosmology is taking the place of God in mankind's need for a "why" '. More particularly, great technological advances have yielded new facts about the heavens. These advances, interestingly, were, in part, a consequence of the Cold War. (Going off at a tangent, it is 'amusing' to note that the end of the Cold War removed a big threat to the West. The US military, in its search for a new enemy, has discovered the potential threat of incoming comets and thus a rich field for new weapons – the nudging of comets from their Earth-impacting orbits.)

Returning to a new public perception, the impact of the string of comet-components on the planet Jupiter brought home the fact that comets *do* collide with planets and the Earth is by no means safe (see Figure 4).

As always, the role of the media is crucial. It is true that, occasionally, a doomsday asteroid collision is postulated, based on some (usually inaccurate) orbit calculations, but biological or nuclear risks are more in the headlines. It is interesting to postulate, cynically, that this might well be because of the media's fixation with laying the blame at someone's door, a person in authority, well-heeled if possible, or the Government. Even a spin-riddled Government cannot be blamed for a cometary impact, although the recent UK Government-sponsored study, referred to already, is perhaps an attempt to get some credit just in case!

To summarize the public's perception of the risk of cometary impact, most people are quite unconcerned but a few, not least those scientists who work in this field, have a degree of apprehension. Although scare-mongering is not intended, it does seem as though more thought should be given to this particular risk and its relation to those other risks of rare but dramatic-when-they-occur phenomena.

How to counter the risk

Most efforts are devoted to the middle-sized objects, say 100 m–1 km in diameter, many of which are asteroids; they are often classed as 'Near-Earth Objects' (NEOs). It is claimed that we know the orbits of only about half these objects, so the first thing to do is to mount a bigger campaign for their detection using dedicated telescopes. Once orbits have been determined, the warning times, i.e. the time before impact, would usually be in the range of years to decades. Two possibilities arise, warning and deflection. Under 'warning', one lists the movement of populations from ground zero (we are considering here city- or county-destroying impacts). With the more likely oceanic impact situation, where giant tidal waves would be produced, populations could be moved from the coastal regions most at risk. One imagines that, over the next century or so, efforts in this area will intensify, albeit slowly; assuming, that is, that there is not an 'interesting' collision in the meantime. Such a collision would concentrate minds wonderfully.

As technology improves it will probably be worth endeavouring to deflect potential impactors, but clearly this is a dangerous game. It is necessary to 'get the sums right' here, and to make a gentle deflection by a space vehicle. Too much force, leading to the disruption of the asteroid or comet could increase the damage to the Earth, not lessen it.

For the biggest objects a possibility is to use military hardware. It has been suggested that a nuclear bomb, exploded some one third of the radius from the Earth's surface would 'boil off' sufficient material to alter the trajectory significantly and to produce a near miss, although some of the bits might still impact.

Some other cometary matters

The cometary rates considered so far are 'conventional' values, but it is not unlikely that a few thousand years ago there was a period when the rate was much higher. It is, in turn, likely that future rates could be much higher from time to time. Indeed, some 30 000 years ahead, a nearby quite massive star will be much nearer the Sun than at present and this will affect the rate of comets coming into the Inner Solar System. The point is that the received wisdom about comets is that there are many billions in orbit round the Sun, extending a quarter of the way to the nearest star. The vast majority go on their way undisturbed but, occasionally, because of near comet/comet collisions or the gravitational effect of nearby stars or giant molecular clouds, some are deflected into the Inner Solar System and thereby pose a threat. It is probably unwise to make plans for foreign travel 30 000 years ahead – it is best to be at home under these circumstances!

Turning from cometary impacts to near misses, the risk of which is clearly much higher, there is contemporary work on the question of the dust brought into the atmosphere by the cometary 'halos'. It seems that about half of the amount of material in the upper atmosphere is from dust 'falling' from outside, and this is variable. The effect on climate variability is not yet understood.

Finally, concerning cometary impacts, there are some good effects! That we (the human race) are here at all can be said to be due, in part, to comets. In the early stages of the formation of the solar system, the rate of impacts was very large indeed and it is likely that some, at least, of the oceanic water was brought in by these 'dirty-ice' bodies, and much of the carbon that is the basis of our chemistry was brought in then as well. Importantly, too, the great collision of 65 million years ago, which killed the dinosaurs and many other species, allowed the mammals to take over. The rest is history …

The Sun

General remarks

The Sun is a star halfway through its life, and thus has about 4.5 billion years to go before running out of fuel. By 1 billion years from now, the solar swelling and associated temperature rise of the Earth will render life as we know it impossible. It will be 'time to go', assuming, that is, that we have not already terminated life on Earth by our own activities. The risks involved in space travel to another, more hospitable, planet, will be very great, but that is another story.

Incidentally, a major argument against intelligent life being common in the Galaxy is to ask why we have not been settled by refugees from planets, in the Galaxy, orbiting around the much earlier stars which had come to the end of their lives. There is no trace of such beings, UFOs (unidentified flying objects) notwithstanding.

Turning to contemporary risks from the Sun, the situation is not clear. Surprisingly, and despite much work, the Sun is not fully understood. That it is not an 'active' star, emitting great outbursts of plasma from time to time, is self evident, the fact that we are here at all shows that. Nevertheless, there is some activity, as evidenced by the observation of sunspots on its surface and small outbursts above its surface seen during solar eclipses. The solar activity is modulated by an 11-year cycle, which we will now consider.

The solar cycle

Everything in the Universe is rotating (perhaps with the exception of the Universe itself) and the Sun is no exception. The sunspot near-surface phenomena associated with the breaking out of pockets of magnetic field have played a prominent part in the development of astronomy. Galileo used the then newly invented telescope to show that they were, indeed, on the surface of the Sun and not an atmospheric phenomenon. The demonstration that the Sun was not perfect, in contradiction to the Church's view that it was, put him considerably at risk from the Inquisition. The risk was compounded by his detection of the (now-called) Galilean satellites rotating round Jupiter (see Figure 3 for an image of one of them – Io). This observation, and others, confirmed the idea of Copernicus that it is the Sun and not the Earth that is at the centre of the solar system. The Earth was thus relegated to a minor planet orbiting a rather conventional star.

The cause of the 11-year cycle of solar activity, a waxing and waning in the number of sunspots and other solar phenomena, is not yet known. What is known is that there have been a plethora of claims for the correlation of sunspot number with 'natural phenomena', from the sex-life of mice to the price of corn. The effect on climate is an interesting one and, since there is an element of 'risk' about climate change, sunspots come within our orbit. For years, the claimed correlation of sunspot number with climate or, more particularly, with short-term weather, was disbelieved. The reason was the lack of an obvious agent whereby the tiny variations of solar output could trigger the atmospheric changes. Help may have arrived however, with the discovery[5] of an apparent correlation of cloud cover over the oceans with cosmic ray activity, which is itself correlated with the solar cycle. This correlation is well-understood and is due to the influence of the magnetic fields in the solar plasma deflecting away charged cosmic rays produced in violent events (shocks from supernovae, exploding stars) way beyond the Sun. Now, the cosmic rays are the main causes of ionization in cloud formation over the oceans. Here is a possible explanation of the climate/sunspot relationship, although it must be said that a number of puzzling features remain, not least the fact that the cosmic ray/cloud correlation is best with low altitude clouds, whereas most of the cosmic ray ionization occurs at high altitudes.

Another low-level effect of the Sun concerns the ozone layer. The risk of skin cancer from the ambient ultraviolet radiation is well known, as is the fact of depletion of the ozone layer by way of man-made emissions, but there are transients associated with solar flares – rare solar emissions related to sunspot activity. The extra risk involved over a few decades is small, but that over very long periods is a big question and one that will be examined in the next section.

Giant solar flares

A number of workers, including the author and Wdowczyk,[6] have examined the risk posed by rare giant flares. The hazard involves not only an effect on the atmosphere but the enhanced radiation level at the Earth's surface and its potential effect on humans. With the giant flares, the destructive agent is the cosmic ray particles (protons, electrons, etc) accelerated in the solar corona (the outer atmosphere of the Sun). Measurements have been possible over the past 60 years or so and a remarkable result appears for the frequency of the number arriving at the Earth. Figure 5 shows the results in terms of the energy at the Earth's surface, as distinct from particle number. Indicated on the figure is the energy density (energy deposited per unit area) needed to wipe out most of the human race, denoted 'radiation catastrophe'. Also shown is the equivalent energy released by the Tunguska asteroid ('Tung'), a full-scale nuclear war between Russia and the US ('NW') and the cometary impact 65 million years ago ('KT'). The cosmic ray data results depend on the particular solar cycle and the results are given for two periods: 1956–60 and 1961–72. These data sets actually refer to the primary radiation and, when allowance is made for loss of energy in the atmosphere and an average is made over time, the bottom line is found. This line can be trusted to about 10^5 ergs per square cm (erg cm^{-2}), for which the frequency is a few per century. At this level there have been conflicting claims as to biological effects on the earth. However, interest is, understandably, at higher energy densities, where biological effects will certainly be present.

It is evident that the line cannot be extrapolated in a linear fashion, otherwise there would be Armageddon every 10 000 years! Theoretical guidance is virtually non-existent and one is left with drawing analogies with other systems. Such analogies suggest an exponential distribution and, in the figure, one is drawn starting from about 10^5 erg cm^{-2}. This line represents the most favourable situation; namely, the least chance of risk. However, even here, seriously damaging flares might well be expected, on average, every 100 000 years. As yet, we have no way of predicting when flares will occur so that the chance of taking precautionary measures (going underground) is remote. However, methods of making predictions are being strenuously sought at present, the driving force being the need to protect satellites and, particularly, their human cargoes. This is one 'risk in space' that is appreciated and is being taken seriously.

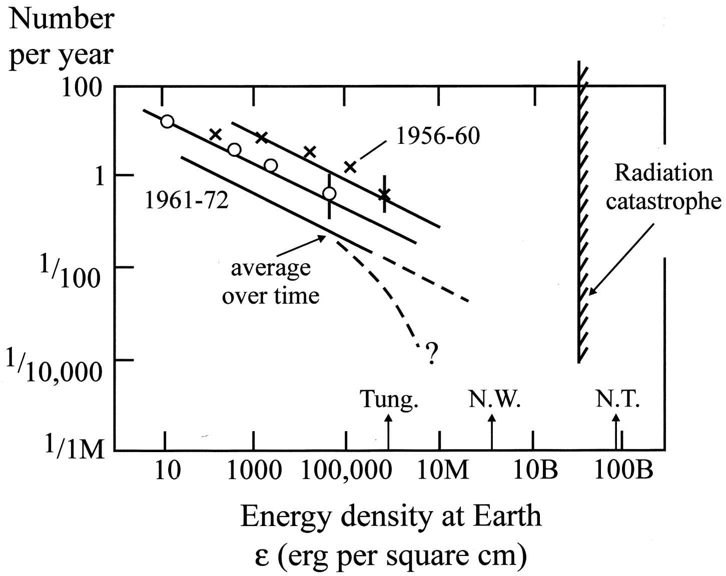

Figure 5. Probability per year of cosmic rays from a solar flare delivering more than an energy *E* at the Earth (the lowest line). A description is given in the text. The dashed line is probably a lower limit to the actual situation. It is unlikely to reach the 'radiation catastrophe' level within the residual lifetime of mankind on earth (10^9 years?). From Wdowczyk and Wolfendale.[6]

Supernovae and cosmic rays

Very close supernovae

A very close supernova, one within about 30 light years, would certainly see us all off and it is evident that there has not been such a close explosion during the Earth's history. Statistically, we do not expect one in the remaining life of the Sun, and Earth,[6] although it is fascinating to note that most of the atoms in our bodies came from the supernova that preceded the formation of the Sun and its planets.

Nearby supernova remnants

The frequency of supernovae is about one per 30 years somewhere in the Galaxy. Assuming uniformity of the number of supernovae per unit area (a sufficiently accurate assumption) this corresponds to about one per million years within a distance of 450 light years. A supernova at that distance would produce a 'gamma flash' which would have an energy density of $\cong 10^5$ erg cm^2. Such a flash is just at the start of the interesting region (Figure 4). The corresponding rate for solar flares at this energy density is about one per hundred years, to be compared with

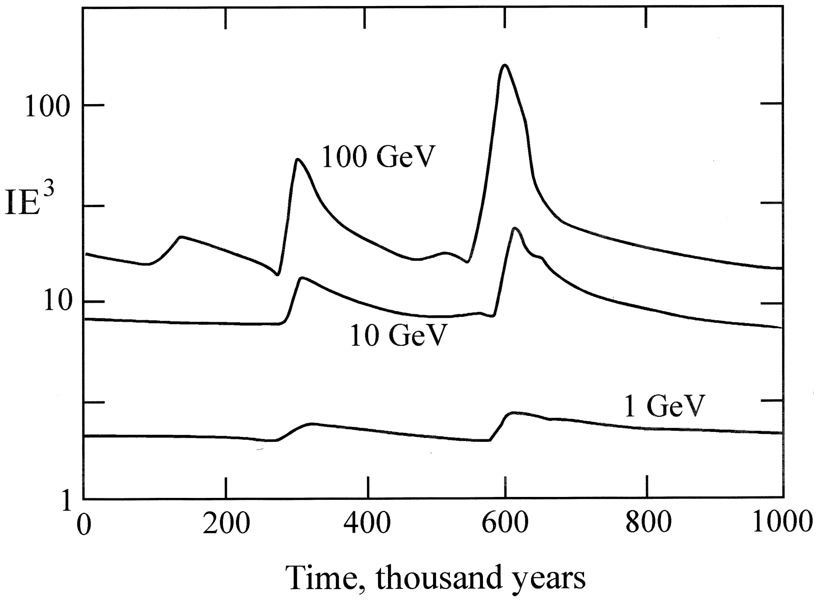

Figure 6. Cosmic ray intensity variations on the scale of thousands of years from Monte Carlo calculations involving acceleration by sporadic supernova remnants, from Erlykin and Wolfendale.[7] Results are given for a variety of cosmic ray particle energies. Those for 10 GeV are probably most relevant to effects on Earth. *I* is the cosmic ray intensity and *E* is the particle energy. The vertical scale is arbitrary.

our one per million years (we have used a 1 Megayear 'window') for supernovae. This example shows how much more important the Sun is, at least for these rather weak energy densities.

Potentially more important are the longer-term intensity changes in the cosmic radiation consequent upon the particle acceleration in supernova remnants. Figure 6 shows 'our' calculations for the intensity changes expected in Monte Carlo calculations involving supernova remnants.[7] It will be noted that over a period of a million years the low energy (say 10 GeV) intensity is liable to increase by a factor of 3 or so. Such an increase is not large in itself but, acting over a considerable period of tens of thousands of years, there could well be significant effects, which could include minor climate change.

Perhaps the biggest effect of a comparatively near supernova (at, say, a few hundred light years) would be psychological. The sudden appearance of a very bright star would point up the risk involved for humans of coasting through the potential minefield that is cosmic space.

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About the author

Arnold Wolfendale is an Emeritus Professor of Physics at Durham University, UK. He has been President of a number of bodies including the Royal Astronomical Society and the European Physical Society. A former Astronomer Royal, his main research is in Cosmic Ray Astrophysics. He, and his colleague Tolya Erlykin from the Lebedev Physical Institute, Moscow, feel that they have discovered the origin of the enigmatic cosmic radiation, a feeling that they have had before! He is a Fellow of the Royal Society.