NEAR EARTH OBJECTS — NEOs

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Recent advances in ground-based, satellite and theoretical astronomy have proved the Solar System's dynamism and complexity — in particular, that some of its minor members, called Near Earth Objects may impact the Earth in the future. In the UK, the USA and Australia, parliamentary interest has been stimulated. This report sets the results of recent surveys in context and considers the risks involved.

THE EARTH IN DYNAMIC SPACE

Near Earth Objects (NEOs) are related to two classes of minor Solar System body – the asteroids and the comets. Their orbits may bring them close to the Earth-Moon system. NEOs vary widely in terms of their composition, size and astronomical history. 'Near' is a relative term, but NEOs can come closer to the Earth than any other member of the Solar System. In 1989, the 300m asteroid Asclepius came to within twice the distance to the Moon[1] but was detected only after its closest approach. NEOs therefore have the potential to collide with the Earth. Given their size and speed, this is a hazard quite distinct from the consequences of human-made objects sent into space returning to the surface[2].

The Earth is by no means isolated in space. Each year it encounters many space objects, though few survive passage through the atmosphere to reach its surface. The smallest and commonest objects are meteors ('shooting stars'). The term 'meteorite' is used to describe those objects that reach the ground. Occasionally a larger object collides with the Earth and, if this occurs on land, an impact crater may occur. The Barringer Meteor Crater in Arizona, USA (**Figure 1**), formed by the impact of a 30 to 50 metre object, is 200 metres deep and 1.2 km wide. Over 150 such craters have now been identified on the Earth's surface (**Figure 2**), with 3 to 5 new ones being discovered each year. Recent years have seen increasing scientific recognition and public awareness that an impact played a major role in a mass extinction event 65 million years ago that saw the end of the dinosaurs. That impact has now been associated with the Chicxulub crater, 200 km across, in the Yucatan Peninsula, Mexico.

Such a catastrophe is neither unique nor necessarily confined to the remote past. Indeed, impact is now discussed as a future potential global threat to humanity. Recent TV programmes and movies have explored this possibility, with varying levels of scientific veracity.

An impact resulting in a global catastrophe is very rare but represents only one end of a range of possible impacts and consequences. From the known population of Earth (orbit) Crossing Asteroids, (ECAs), the numbers in each size range can be estimated. There is a rapid increase in numbers at smaller sizes (**Table 1**).

TABLE 1 BEST ESTIMATES FOR NUMBERS OF EARTH (ORBIT) CROSSING ASTEROIDS (ECAs) OF VARIOUS SIZES

Diameter	Number
larger than 1.0km	1000 to 2000
larger than 0.5km	4000 to 8000
larger than 0.05km	0.5 to 1.5 million

An asteroid hitting the Earth would be moving at up to 25 km per second (90,000 km per hour) a comet even faster. For comparison, the Earth moves at 29 km per second in its orbit, while a jet airliner manages only about 0.2 km per second. An impacting object's energy release depends on its mass and speed, so that an object only 10 metres across, but moving at such a speed, has the energy of about 5 times the Hiroshima bomb (which had the explosive force of about 15 kilotons [of TNT]).

In recent years, there has been a rapid increase in the numbers of NEOs detected in astronomical surveys. The conviction has also grown that such survey work should be done, not solely for scientific interest, but with the aim of establishing an inventory of NEOs with a diameter of a kilometre or more within the next decade, so that the risk of collision with the Earth can be assessed more accurately.

FIGURE 1 BARRINGER METEOR CRATER, ARIZONA

Photograph: National Aeronautics and Space Administration, (NASA)
Estimates of the crater's age range from 10,000-50,000 years.

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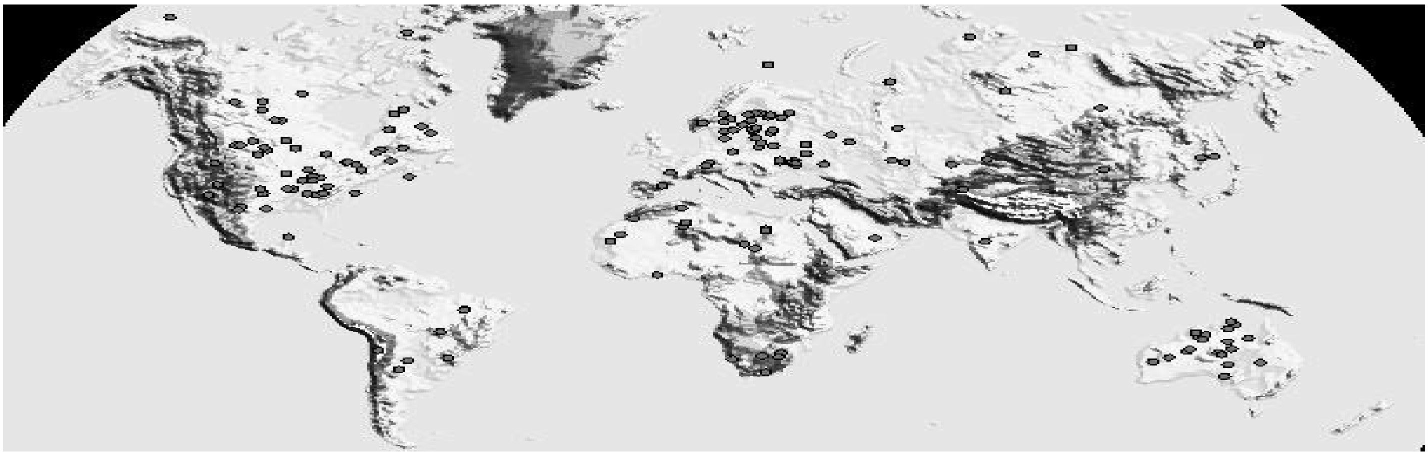
[1] 1994 saw the closest recent Earth approach by an asteroid, to within 100,000 km, by object 1994XM (about 10 metres across).

[2] See POSTNote 80, *Impacts on Earth from Space,* June 1996.

FIGURE 2 DISTRIBUTION OF IDENTIFIED TERRESTRIAL IMPACT CRATERS



Source: Natural Resources Canada, Geological Survey of Canada

The uneven distribution of sites reflects the unequal amount of research investigation in different parts of the world, and differences In the ease of detecting crater structures due to surface geological or vegetation characteristics.

Any object of that size or larger striking the Earth would almost certainly cause a global catastrophe, mainly due to the effect of the impact on climate. The survey work, known as the 'Spaceguard' survey, is intended to be an international effort, although at present almost all the work done is funded, publicly and privately, from within the USA.

Technical terms used in this report, especially the categories and features of Solar System members, are explained in the Appendix, forming the second section.

DETECTION OF NEOs

The astronomical search for NEOs demands detection of very faint objects, as they are not only small but also usually reflect sunlight poorly. Such searches will also reveal many other objects -- NEOs are only a minority of the objects detected in any Solar System survey. The Minor Planet Center (MPC), at the Harvard-Smithsonian Center for Astrophysics acts on behalf of the International Astronomical Union (IAU) as the world centre for the collection and collation of orbital measurements for 'minor bodies'. It receives detailed records used to determine the orbits of several new comets, a thousand asteroids and tens of ECAs each year.

Current survey systems, such as the Spacewatch survey at the University of Arizona, use telescopes of about 1m aperture and electronic charge-coupled device detectors (CCDs)[3]. To detect very faint objects, the same region of the sky is scanned several times. On the resulting images, stars remain as fixed points but any solar system object will move across the background of stars and so appears as a short line on a single scan (if the exposure is long enough), or will have noticeably changed its position on successive scans (see **Figure 3**).

A major recent advance has been increased automation of asteroid and comet searches. If a possible object is detected in one scan, others are used to confirm that it is real and not an error. The Spacewatch programme has been a proving ground for this approach. Previously, astronomical survey work tended to use photographic plates. These first required processing and then scanning by eye or digitising for computer based analysis. This work often severely lagged the photographic survey. CCD systems give a faster record of a possible detection and hence follow-up observations can be undertaken. A newly-detected potential NEO is visible for only a limited time, putting a premium on fast systems for identifying candidates for more detailed follow-up and on the ability quickly and systematically to search archives, to see whether an object was recorded earlier.

The detection process yields an initial measurement of an object's rate of motion across the sky. If the detected object is a Main Belt asteroid this will lie within a characteristic range. As potential NEOs have orbits bringing them closer to the Earth, they can appear to be moving faster and therefore stand out. Unfortunately, in some parts of their orbit, potential NEOs may well have a relative motion similar to Main Belt asteroids, so that the need arises for long-running surveys over large areas of sky. Follow-up observations spaced over about a week allow the orbit and its relationship to the Earth's position at any time to be determined. Only at this stage is it possible to consider whether the new object is, for example, an ECA or a comet.

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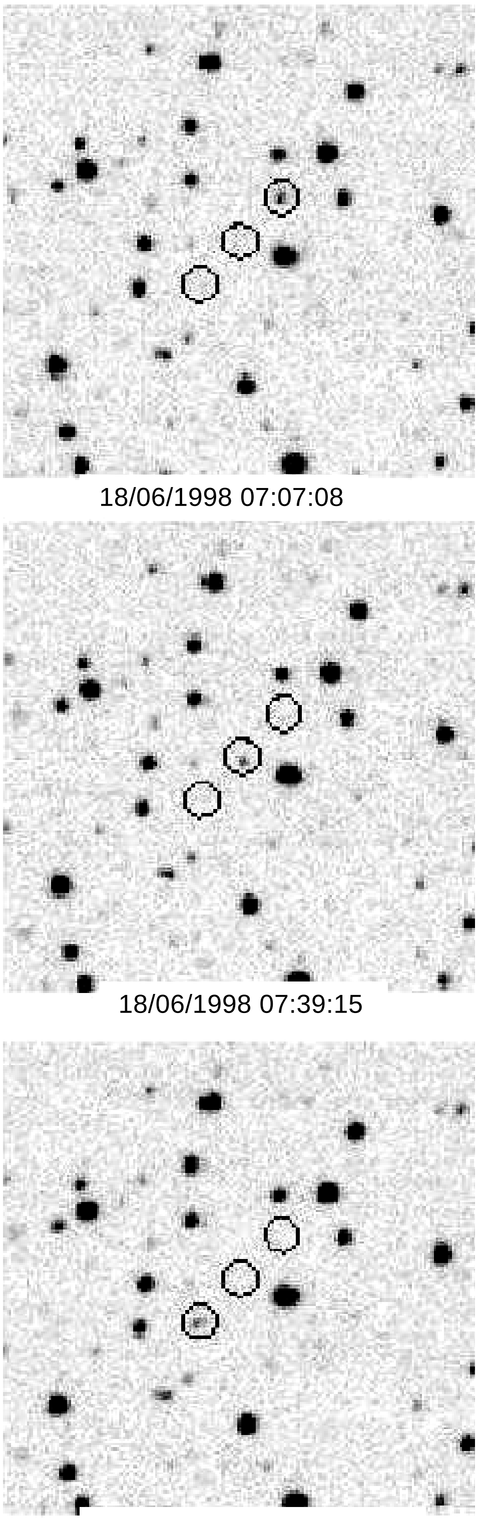
[3] These are similar to image-recording arrays in digital cameras.

FIGURE 3 DETECTION OF NEO 1998MQ BY THE LOWELL OBSERVATORY, FLAGSTAFF, ARIZONA



18/06/1998 07:07:08

18/06/1998 07:39:15

18/06/1998 08:10:28

Photograph: LONEOS Programme, Lowell Observatory, Flagstaff, Arizona, USA

The three frames show the movement of the object over a period of roughly an hour, from top right to bottom left of the photographs, with its three successive positions ringed on each of the frames. 1998MQ was first detected on 4 June 1998 but its apparent rate of movement at that time did not suggest it was a NEO. This sequence of photographs, taken on 18 June 1998, showed that it was.

Detection initiatives

In 1992, NASA published its Spaceguard Survey Working Group report[4]. This outlined plans for a survey, using purpose-built telescopes, to identify 90% of ECAs within a decade. There is a strong scientific case, independent of any hazards they pose, for increased understanding of the Solar System's minor bodies, as they hold clues to its origin, the formation of planets and the evolution of all its members. For this purpose, it is not, however, necessary to have a catalogue of *all* such objects. The aim of the NASA plan (as its name suggests) was therefore specifically to address the impact risks associated with ECAs.

Subsequently, lack of funding has led to a move away from the original concept of dedicated and identically-instrumented sites, towards the flexible use of existing equipment, e.g. by adding new detectors to a current telescope[5]. Even at the most favourable observing sites, detecting faint objects is possible during only about two weeks in each month when the Moon is not too bright. A 1995 NASA report showed that for NEO detection it is better, (at an individual site), to aim for an all-sky survey every month, rather than just part of the sky, even if the minimum brightness detected has to be compromised.

At any one site, some regions of the sky never become visible. There is a particular dearth of observations in the Southern Hemisphere, with only one current NEO detection programme – in Australia. The Anglo-Australian Observatory at Siding Spring, Australia, made major contributions to surveys from 1990 to 1996. US and Australian funding for the programme then ceased, although some digitising of photographs taken in Australia continues in the UK.

IMPACTS AND CRATERS ON THE EARTH, THE MOON AND BEYOND

The scars of many impacts show as craters on the Moon (**Figure 4**), with the far side, visible only by satellite photography, being more heavily cratered. Unlike the Earth, the Moon lacks an atmosphere and the partial protection it affords. The Earth and the Moon have shared an orbit around the Sun for at least 4 billion years, ever since the Moon was formed, most probably by the collision of a Mars-sized object with the Earth.

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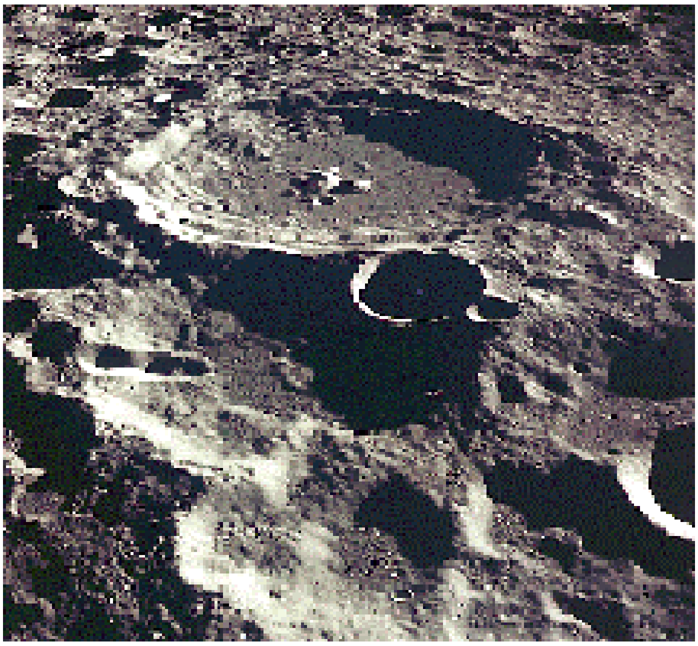
[4] See http://impact.arc.nasa.gov/reports/spaceguard/index.html.

[5] The original Spaceguard project was costed at US$50 million capital costs and US$10 million annual operating costs, in 1993 US$.

The cratered surface of the Moon therefore shows that the Earth also must have experienced a similar impact history[6]. On the Earth, erosion and tectonic activity have removed much of the evidence for earlier impacts. Furthermore, unlike the Moon, over two-thirds of the Earth's surface is covered by water. Most of the 150 or so impact sites that have been identified on the Earth's continents (Figure 2) are geologically 'recent', i.e. they have occurred in the last 200 million years.

FIGURE 4 CRATERING ON THE MOON'S FAR SIDE



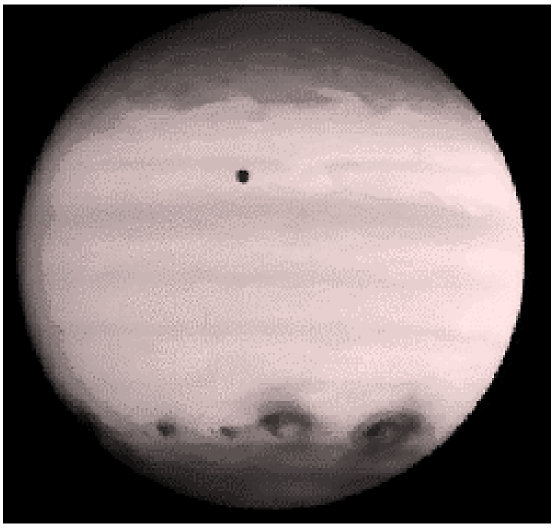
Photograph: NASA – Apollo 11 mission, 1969

The 'chain of craters' at about 8 o'clock in the photograph may represent a multiple impact event.

Not only does the Moon record past impacts – seismometers left there during the Apollo landings have registered recent surface impacts, as well as internal seismic activity. There is considerable evidence that some impacts on the Moon and other members of the Solar System have occurred closely grouped in time. This suggests that the impacting objects were clustered along an orbit.

A spectacular confirmation of impact processes occurred in July 1994 when about 20 fragments of the Shoemaker-Levy 9 comet collided with Jupiter (see **Figure 5**). This event vividly corroborated telescopic and satellite evidence that *all* objects in the Solar System have experienced significant collisions, which continue today. After an initial heavy bombardment about 500 million years after their formation 4.5 billion years ago, the inner planets, including the Earth, have had a much lower, but roughly constant rate of impact for the last 3 billion years. However, the residence times of both ECAs and short period comets in the inner Solar System are much shorter. Therefore, to maintain this constant rate, those lost by impact must be replaced at about the same rate by objects coming from the Solar System's outer parts.

FIGURE 5 IMPACT SCARS OF COMET SHOEMAKER-LEVY 9 ON JUPITER, JULY 1994



Photograph: NASA – Hubble Space Telescope

Traces of the impacts of several cometary fragments lie in the lower hemisphere. The dark spot in the upper hemisphere is the shadow of Io, one of Jupiter's moons.

Impact craters on the Earth have at least two types of structure, determined by the size of the impacting object, though they are not always easily recognised. The simple craters, with a bowl shaped depression and a raised rim, are about 20 to 30 times larger in diameter than the impacting object. The final crater is partially filled in by material ejected in the impact so that if any fragments of the impacting object survive they are buried. Meteor Crater, Arizona (Figure 1) is a classic example of this kind and stands out as it is in a vegetation-sparse desert landscape. It is relatively recent and so has been subject to little erosion.

If the incoming object is larger than about a half kilometre, the crater shape is more complex. The impact, if it could be seen in slow motion, would look like a water droplet landing in a puddle. In the largest impacts, a central peak is raised and ripples spread across the liquefied rock surface. These are preserved as the rock solidifies before the surface flattens. For these craters, the overall width of the ring-like structures that result is very much greater than the crater depth. The crater at Chicxulub, which is not evident on the ground and has been identified by geophysical mapping techniques

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[6] An area of the Earth will actually have more than ten times the risk of the number of impacts as the same area of the Moon, because of the Earth's stronger gravitational field. However, the Moon's lower gravity means that the traces of an impact are scattered over a much wider area than occurs with an equivalent object striking the Earth.

used for oil prospecting, shows a series of ring features extending to at least 270 km in diameter.

Surface craters are not the only evidence for impacts on the Earth. Because of the high speed of an impacting object, the temperature and pressure at its point of contact with the surface are instantaneously raised to high values (8-10,000°C and 10-900 gigapascals [GPa][7]). This fragments and vaporises both the impacting object and the local rock. A shock wave passes through the underlying rock leading to very characteristic metamorphic changes in its crystal structure that can be used to detect impact events.

BOX 1 THE 'TUNGUSKA EVENT', SIBERIA, 1908

On 30 June 1908, a massive aerial explosion occurred over the remote Tunguska area of central Siberia, (62°53'N, 101°54'E), about 600 km north of the city of Krasnoyarsk. Even though in this event no crater was formed and it appears the object (now considered to be a 'carbonaceous chondrite' type asteroid [see Appendix]) exploded in the air, between 6-10km from the surface of the Earth, ground damage was very extensive - with trees totally destroyed over a roughly circular area of radius 25km, covering some 2000 km^2, more than six times the area of the Isle of Wight.

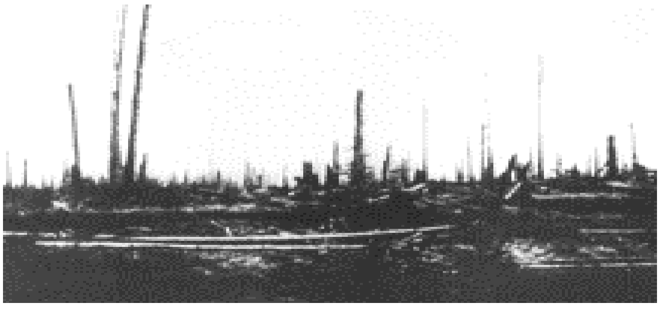
Estimates put the size of the object at 50-100m diameter, its mass at around 100,000 tonnes and the energy released by the explosion at 10-40 megatons, 500-2,000 times that of the Hiroshima bomb. Large quantities of dust were injected into the upper atmosphere from the object itself, the blast wave's impact with the surface and the subsequent forest fires. The effects of this were seen worldwide for some months after the event, in the form of spectacular sunsets and bright night skies.

The remoteness of the area and the difficulty of the terrain, meant that the incident was not initially investigated scientifically until 1927, while the subsequent history of the Soviet Union seriously limited further work. Only recently has significant investigation been possible, with a major international expedition planned for July 1999. Among other activities, this will investigate bottom sediments in a lake 8km from the explosion 'ground-zero'.

There is no undisputed evidence of any macroscopic remnants of the Tunguska object reaching the earth. It is known that its approach angle was 30-35° to the horizon (hence the fact that it was observed travelling over a distance of more than 1000km across Siberia). This has led to suggestions that part of the asteroid might have skimmed through the atmosphere before returning to space.

There remains some scientific uncertainty about the exact nature of the Tunguska event. While the main disagreements centre on the type of the incoming object (asteroid or comet), its size and details of its dynamics, some commentators have advanced non-celestial (e.g. seismic) explanations for the surface effects. There have even been various exotic, non-scientific, theories attributing the event to activities of extraterrestrial intelligent beings.

Less well-known than the Tunguska event, a similar forest strike, possibly of three objects in close succession, occurred in western Brazil in August 1930. There was also an event in Guyana in 1935.



Photograph of the epicentre (ground-zero) of the Tunguska event explosion taken by L.A. Kulik in 1927.

Note that because the explosion occurred vertically above this point, at least some tree trunks were left standing, though completely stripped of their branches. Further away from the epicentre, trees were blown over, their trunks pointing away from the centre of the explosion.

CONSEQUENCES OF IMPACT

All objects less than about 10m across and stony objects up to about 100m diameter are likely to be destroyed in the atmosphere. Iron objects of this scale are likely to break up but some fragments can survive to impact the ground, producing craters in the order of one metre in diameter and possibly with several spread over an area of few square kilometres. About one event of this type occurs a decade[8], but usually in the ocean or away from inhabited areas, given the relative sizes of these parts of the Earth's surface. Every hundred to a thousand years, an incoming object about 50m across impacts on the Earth. This is in the size range of the iron object that formed Meteor Crater, Arizona and the object that caused the 'Tunguska event' (see **Box 1**).

For objects 150 to 350m across, the impact rate decreases to once in 5,000 to 15,000 years. Stony meteors this size will also reach the surface. Increasingly large land areas would be affected by the collision, while an impact of this size range and above in the ocean leads to a significant threat of damage by tsunamis[9] (see next section).

For a 1 in 100,000 year event, the size of the impacting object increases to over a kilometre across. Such impacts could well have a global significance. This is due to the injection of very large amounts of dust and/or water vapour high into the atmosphere, leading to prolonged daytime darkness, a cooling of the Earth's surface, and

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[7] The sun's surface is around 5,500°C. The highest sustained human-made pressure achieved is 170GPa. 100GPa is 1 million times average atmospheric pressure.

[8] A rate of "once in x years" does not mean that the time between impacts will be exactly x years, but that over many such events the *average* interval will be x years.

[9] These are large waves, sometimes erroneously called 'tidal waves'. Tsunamis may also be generated by submarine earthquakes and cataclysmic undersea or volcanic island eruptions and by submarine landslides.

the death of much vegetation. These effects scale up as the size of the impacting object increases, to the 10 km impact object, once in 10 to 100 million years, which would produce an event similar to the consequences of the Chicxulub collision.

OCEANIC IMPACTS

Despite featuring in some of the media focus on NEOs, oceanic impacts are comparatively under-researched. The main research centres are Los Alamos and Sandia National Laboratories, both in New Mexico, USA.

Any incoming object is over twice as likely to hit water, which covers 71% of the globe, as land. Such impacts are much more difficult to identify than those on land. Only one has been established conclusively – a strike over 2 million years ago by a 1 km size object in the Bellingshausen Sea, to the west of the Antarctic Peninsula, identified by submarine iridium and seismic anomalies.

The age and distribution of oceanic impacts must be similar to those of land objects shown in Figure 2. This suggests that continental shelf areas have received at least 25 impacts of comparable objects over the past 200 million years. Such impacts, even if not those occurring in the deep ocean, could lead to marked tsunami effects on adjacent shores. Some coastal areas are at greater risk from impact-caused tsunamis than from land impacts. Coastal locations near the Chixulub crater show traces of huge tsunami effects and many other locations have geological evidence of marine-originating rock fragments suddenly being deposited many metres above the sea level at the time. However, as noted, earthquakes and oceanic and island volcanic eruptions,[10], may also cause tsunamis, making it difficult to relate evidence to any particular source event or to separate terrestrial from extra-terrestrial causes.

The dynamics of oceanic impacts are not well understood. Media accounts have featured walls of water several kilometres high. The highest tsunami historically recorded (earthquake-caused) was about 80m high in the Ryukyu Islands, Japan. Both submarine and coastal topography affect the 'run-up height' of a tsunami[11]. (its height at the furthest distance travelled inland) In 1958, a terrestrial landslide-induced tsunami in Alaska had run-up effects over 500m above sea level.

ISSUES

Recognition of the existence of NEOs and their role as potential impactors on the Earth has gathered momentum over the past 20 years. The association of the Chicxulub crater with an 'extinction level event', the numerous other terrestrial impact craters found and the realisation, from interplanetary exploration, of the significant role of impacts throughout the solar system, have driven this. Studies analysing the indirect damage from a large-scale nuclear exchange have shown how a NEO impact could be globally devastating, because of its secondary effects on the atmosphere and life forms.

The need for international effort

Almost all recent NEO discoveries have been by US-based observers[12] from a range of organisations funded by NASA or the US Department of Defense, but including some private individuals. The USA is not proportionately more prone to damage from NEO impacts than any other location, nor it is possible to predict exactly where on the Earth an incoming object will strike until very soon before impact. Impacts could well have effects over very large areas, rendering national boundaries insignificant. Researchers in other countries have advocated more international effort. Some are concerned that the defence establishment of a single nation dominates the work. At both professional and political levels, there is strong US support for wider international involvement in NEO *detection*, though less for it in any NEO *destruction/deflection*, activities.

As already noted, there is very little detection work in the Southern Hemisphere, although observations there would directly complement those from Northern Hemisphere sites.

In 1996, the 'Spaceguard Foundation', based in Italy, was inaugurated to promote general international collaboration and, in particular, a complete survey of NEOs greater than 1 km in diameter within the next decade. A UK affiliate is one of several national associate bodies.

Soon after the controversy over the March 1998 announcements about NEO 1997XF$_{11}$ (see **Box 2**), Spaceguard UK issued an open letter to the Minister of State for Science. It argued that the 'current lack of interest or policy relating to the threat of cosmic impact' in the UK led a failure to reassure the public and arose because the UK does not currently fund 'substantial research' in the area.

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[10] An example is Krakatoa in 1883, a 1 in 100 year event, estimated to have released 100-150 megatons of energy.

[11] Evidence suggests that gentle continental shelves (e.g. as around the UK), tend to dissipate tsunami effects. Most at risk are coasts with adjacent deep water.

[12] Several are originally from the UK.

BOX 2 NEOs 1997XF$_{11}$ AND 1999AN$_{10}$: TWO RECENT EXAMPLES OF ANNOUNCEMENT DILEMMAS

NEO 1997XF$_{11}$ (an ‘Apollo’ asteroid, see Appendix, **Figure 8**) was discovered on December 6, 1997 by the University of Arizona Spacewatch Programme. Early calculations of its orbit and an estimate that it was 1-2 km across, led to its designation as a ‘Potentially Hazardous Asteroid (PHA) (see Appendix).

Early observations suggested that 1997XF$_{11}$ would approach the Earth to around 800,000 km in October 2028. Further observations on 3 and 4 March 1998, led to the IAU issuing a circular on 11 March that 1997XF$_{11}$ would pass the Earth at 46,000km on 26 October 2028. The error in the estimate gave a possibility of about 1 in 1000 of collision. An accompanying IAU press release noted the uncertainties in the computations, stating (in the first paragraph) that the ‘chance of an actual collision is small, but one is not entirely out of the question’, and (in the sixth paragraph) that it was also ‘possible that 1997XF$_{11}$ will come scarcely closer than the moon’.

This release received widespread media attention. Typical was a headline from the BBC’s online news network – ‘Celestial bomb heading for Earth’. The figure of a 1 in 1000 chance of actual impact with the Earth was widely quoted.

The next day, researchers at the NASA Jet Propulsion Laboratories in California reported that not only had archival photographic evidence been uncovered, taken in March 1990, which greatly increased estimates of the distance of nearest approach but, *even without this*, the 2028 ‘impact probability would be zero’. Including the archival evidence gave a nearest approach of 960,000 km at 08:00 GMT on 26 October 2028.

The IAU issued a further circular the next day, reporting these calculations. Press comment was encapsulated by one agency’s headline: ‘Baby boomers, breathe easy. Your retirement will not be ruined … and your grandchildren will be safe’.

Although some researchers had already warned of the dilemmas that public reporting could create, it took this experience to provoke a concerted attempt by astronomers to systematise reporting conventions, although NASA has already introduced procedures to be used by researchers receiving its funding, with the sanction of loss it if they are not observed.

Some researchers feel that the constraints of such procedures led to an incident in March 1999, when an Italian team calculated that object 1999AN$_{10}$ would make a 2039 close approach, with a very small risk of impact and a succession of approaches over the next 600 years. There were allegations that there was a ‘voluntary or externally imposed veil of secrecy’ placed over this possibility, which they felt should have received wider publicity.

Some commentators believe that the UK could support detection work similar to the US LINEAR programme (see Appendix, **Table 3**), which currently identifies about 150 relevant objects a year. To locate the estimated 4 to 8,000 ECAs down to 0.5 km in size, LINEAR will there-fore take around 40 years, a time that could be halved by a parallel effort.

Moral justifications are also advanced for more effort – especially that the detection and possible deflection of extinction-threatening NEOs is the only such threat where humankind could potentially take action to ensure its own survival and maybe that of all life on Earth.

The dilemmas of announcing detection

The payback of a Spaceguard survey is that, for any potential asteroid impact, there would probably be a long lead time, perhaps several decades, between detection and potential impact (as with initial estimates for NEO 1997XF$_{11}$). Short period comets and their rocky remnants would remain a concern, requiring continuing observation of the entire sky. Although fewer than asteroids, they (and long-period comets -- a considerably lesser risk), are much faster moving and so have a greater impact energy[13]. The period between their detection and potential impact could be only months.

It is probable that, at some future date, detection efforts will lead to prediction of an actual impact on Earth. If the object is an asteroid, in the time between initial identification and potential impact, it could complete many orbits, making recurrent near approaches to the Earth (see for example, object Toutatis, in Appendix, **Figure 10**). This could cause minor perturbations in the asteroid’s orbit, increasing uncertainty about the likelihood, and even more, precise time and location of an impact.

Historically, astronomy has had a strong presumption in favour of the earliest public announcements, in part to encourage follow-up observations, but also through a general tradition of communicating new discoveries widely[14]. This is encapsulated in a statement made by the IAU after the 1997XF$_{11}$ incident that ‘information must be promptly conveyed to the governments of the world’[15] (see Box 2).

Prediction will inevitably be a probabilistic process, with many remaining uncertainties. The effects of atmospheric interactions with the shape and composition of smaller impacting objects[16], including the important consideration of whether an object would fragment, are essentially unpredictable,. This would make it extremely difficult to pinpoint the actual impact site(s) until very soon before occurrence.

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[13] Estimates suggest that short period comets comprise only 1% of the total number of objects of concern but up to 25% of the potential impact energy. The proportion attributable to long period comets is very small.

[14] With comets, there is competition to have a newly discovered one named after its confirmed discoverer.

[15] The IAU presumption in favour of communication to *government* (as opposed to, e.g priority for Web dissemination) is based on the belief that governments ‘may be in a position to organise countermeasures’.

[16] Objects larger than about 5km are unlikely to be affected significantly by the Earth’s atmosphere.

As with prediction of threatening terrestrial events, such as the occurrence of earthquakes, severe dilemmas may arise because of uncertainty and the risk of false alarms. The economic cost of disruption, if people over a very wide area take avoiding action, could approach or even exceed the actual damage cost, especially if the impact finally occurred in an uninhabited or lightly inhabited area. An asteroid impact prediction with a period of decades between detection and the event, would most probably trigger an all-out programme for intervention, while a predicted impact within a time that precluded any intervention[17] could lead to various forms of fatalistic behaviour. If it were for a highly imminent event, it could even precipitate a major breakdown of social and economic institutions, such as a run on banks as people sought to spend savings. Press headlines like those at the time of the 1997XF$_{11}$ incident (Box 2), led to various suggestions (e.g. on web sites) that people should indulge themselves while they still could.

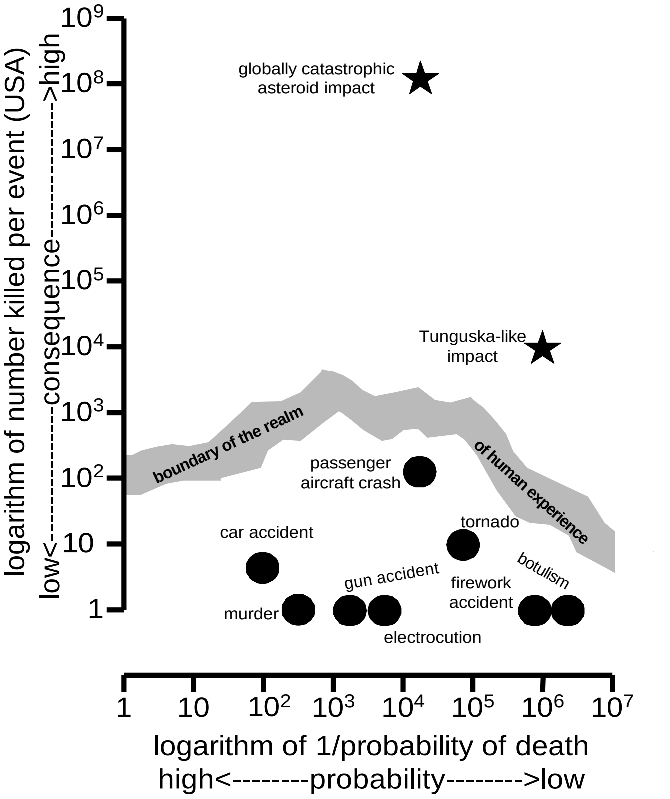
Even with a warning of decades and a presumption for intervention, major uncertainties would remain – such as how close to the Earth would need to be a predicted approach before committing to an intervention programme, which would cost, at the least, hundreds of millions of pounds. A decision on commitment would undoubtedly be influenced by the size of the potential impactor and the margins of error in estimates of its track. Another dilemma is the classic 'crying wolf' syndrome, where a series of 'false alarms' (as statements made on a probabilistic basis may inevitably turn out to be) would lead to cynical rejection of a later warning that was, in fact, valid.

The 1997XF$_{11}$ incident spurred the IAU to work on a set of recommended procedures to be followed when discoveries lead to predictions of potential impact by the MPC. The IAU intends that these will conform to the following general principles:

- All information will be openly shared with astronomers and the general public worldwide.
- The content of public statements that might 'alarm the public' will be subject to prior scientific peer review by the IAU.
- IAU Officers and 'appropriate authorities' will be consulted before information is released to the press.

There is no guarantee that predictions of impact would be made through the IAU-MPC system. NASA has already introduced reporting conventions that it requires all researchers receiving its financial support to observe. Some commentators feel that such procedures are too bureaucratic and, in a short 'detection to impact' case, could lose valuable 'warning time'. Others (and one recent 'impact movie') have suggested that fears about social disruption might lead governments to suppress information about an impending impact, perhaps justifying this on the grounds that there would be little that could be done anyway, at least in a short detection to impact case. Professional astronomers, however, believe that it would be very difficult to prevent information from reaching the public domain.

FIGURE 6 DEATHS PER INCIDENT AND PROBABILITY OF DEATH BY INCIDENT FOR TWO TYPES OF NEO IMPACTS AND VARIOUS OTHER HAZARDS



Source: modified from *Nature*, **367**, 38, 1994

BOTH AXES ARE **LOGARITHMIC** SCALES – that is, each division on the axes indicates a value TEN TIMES greater than the one below it.

It has been suggested that an index system should be used to systematise any predictions that are made public. This would attempt to deal with the fact that 'it will not be possible initially to preclude a nonzero collision probability for many close approach events occurring within the next century' – in other words, that most announcements would inevitably later be shown to be false alarms. An index would need to embrace two dimensions – the probability of the event occurring and the severity of the consequences if it did – as measured by the energy of the impact. Probability of impact would be on a scale of 0 to 5, with a 0 rating being a probability of less than one in 100 million and a 5 being one in 100 or more. Consequences would be assigned to one of four classes – a) no consequence (harmless atmospheric

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[17] A short or long period comet might give very little time.

disintegration likely); b) possible local impact damage; c) severe local and possible regional damage and d) severe regional damage and serious global effects. The value of such a system would probably depend on it being reasonably widely propagated and understood *before* any specific use were made of it in a predictive announcement.

Assessment of risks

The alleged risks of an individual being killed by a NEO collision are often compared with those of other fatal hazards, or with low probability events (such as 'winning the National Lottery jackpot'). Sometimes, estimates of deaths are converted to monetary values, (using standard values of human life), to derive cost-benefit ratios to justify a particular strategy. Most estimates use data in a 1994 article in the journal *Nature* [18].

Risk data are usually given on a unitary scale, often accompanied by statements such as that the risk of being killed by an asteroid is 'greater than of being killed as a passenger in an aircraft crash', etc. For example, a scale given in the *Nature* article, presents (for the USA), the chances of death from a firearms accident as greater than from asteroid/comet impact, which in turn are greater than from a tornado, or from botulism food poisoning[19].

The validity of such comparisons for policy purposes has, however, increasingly been questioned[20]. **Figure 6** shows a two-dimensional plot, with, on one axis, consequences (numbers killed) if an event occurs and, on the other, the risk to an individual of dying from that event. Risks from NEO impacts lie in a very different area than other, 'familiar', risks. In fact, they lie totally outside the realm of events with which humans are familiar. Comparing very low-frequency/very high consequence events (such as a NEO impact), with high probability/low consequence events, (such as fatal car accidents), as well as involuntary with voluntary risks, may not be an effective way to seek public support for an activity.

Another approach to risk assessment does not try to estimate fatalities but simply the chances of an individual location on earth being within the devastation area of an impact, for a given size of object. For a 'Tunguska event', with an estimated frequency of 1 in 100 years, the annual risk has been calculated as around 1 in 25 million.

Lower size limit to a comprehensive search

The rationale for concentrating any systematic search for NEOs on those above 1 km across is that it is these that could cause an 'extinction level event'. Also, some risk studies that use monetary assessments of the damage resulting from various hazards suggest that it would be more cost-effective to concentrate efforts on dealing with various terrestrial hazards, than on trying to deal with smaller NEO impact consequences. Furthermore, with current technology, only a very small proportion of objects under around 200m across can be detected until very soon before potential impact. A systematic detection programme for smaller objects would require commitment of more resources.

Conversely, while maybe not globally threatening, impact effects from smaller objects, especially if affecting a populated area, could be significant – and their chances are greater, so that the NEO incident most likely next to occur will be on this scale.. Some commentators therefore believe that the size threshold for a systematic detection programme should be lowered

Intervention responses

Prediction of an impact many years in the future would provide time to consider a technological response – including possibly an attempt to deflect a NEO from its Earth-threatening path or to fragment it to small, harmless pieces. A very important consideration is that the longer the time between any active intervention and the potential Earth impact, the smaller the force of the intervention required, at least for deflection. This places a premium on comprehensive early detection.

Several deflection strategies have been suggested. For small (100m) NEOs, direct impact by a mass of 100 to 1000 kg could produce a sufficient change in its velocity, without needing any explosive. For larger objects, a nuclear detonation close by has been suggested[21]. This would vaporise a thin layer of the surface, producing a short-lived jet of material. The resulting small change in the speed of the asteroid could modify its orbit from a collision course. For objects greater than 3 km across, recent work suggests that surface detonation would be the most effective way of achieving deflection.

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[18] C.R. Chapman & D. Morrison, *Nature*, 367,33-39, 1994

[19] The risk estimate assumes the impact of an object over about 1.5 km across, which is taken as being a 'global catastrophe'' event, leading to the deaths of over 1.5 billion persons and occurring with a frequency of 1 in 500,000 years.

[20] See POST report 81, *Safety in Numbers? Risk Assessment in Environmental Protection,* June 1996, p 12-16.

[21] An explosion alongside the object might simply impart spin, without affecting its orbital speed. Detonation in front or behind, fractionally to slow down or increase it, affecting the time and distance of closest approach, is preferable.

Such schemes assume that the NEO is a coherent body. Some asteroids seem to have had proportionately enormous impacts (see Appendix, **Figure 11**) yet have not fragmented. Instead, they may have fractured into a porous 'rubble pile' that has not dispersed. A detonation close to such an object would be similar to kicking a pile of pebbles and expecting all to move uniformly.

An alternative approach is to try to fragment any object to remnants less than 10m in size[22]. This may be especially appropriate for objects under 0.5 km across. A surface explosion would not cause pulverisation – it would need to be inside the object. Such a process would be uncertain, unpredictable and considerably more complex technologically than strategies relying on close or surface detonation.

The UK has particular expertise in three areas relevant to deflection/fragmentation – the modelling of asteroid and cometary structures, their dynamics and the effects of nuclear detonations. It could therefore make a particular contribution to any international effort, both in developing general competence and in devising a specific plan, were a potential target object identified.

It has been suggested that deflection techniques could be used to alter the trajectories of asteroids or comets *deliberately* to bring them closer to the orbit of the Earth. The primary aim would be to use them as a source of raw materials for space exploration. This is not because they contain materials unavailable on the Earth[23] but because the very low speeds needed to leave the surface of the object mean that the energy used to move material would be far less than in putting the same amount of material into space from the Earth, thus reducing costs.

Nuclear detonations in space

Many discussions of intervention strategies make almost casual reference to nuclear explosions to deflect or fragment threatening objects, although the launching into, and the use of nuclear weapons in, space is a highly controversial strategy. The assumption seems to be made that the threat of Earth collision would overwhelm any opposition to such strategies. The uncertainties surrounding impact predictions would undoubtedly receive intense scrutiny before this could occur. Some commentators argue that the retention of nuclear capability, ostensibly to deal with NEOs, would be destabilising to disarmament efforts, and consequently would be a greater risk than that of potential NEO impact itself. They also often suggest that advocates of using nuclear explosions to defend against NEOs are seeking the continuation of nuclear weapons in general.

Placing nuclear weapons in space would conflict with the 1967 'Outer Space' Treaty and the 1963 Partial Test Ban Treaty, and arguably with other international agreements. It has been suggested that treaties could be modified to allow the stationing[24] and/or use of nuclear weapons in space beyond 160,000 km from Earth. Apprehension would be allayed if any such system were an international effort. It has been further suggested that any nuclear explosive delivery systems so installed should be designed to be incapable of surviving penetration through the Earth's atmosphere to a level above the ground where they could cause damage, e.g. by not being fitted with heat-shielding surfaces.

Another concern attaches to the launch failure risk of a spacecraft carrying a nuclear device. Even though such a failure may not carry the risk of a nuclear detonation, possible ground contamination by nuclear material is a non-trivial risk, as accidents involving loss of nuclear weapons from aircraft have demonstrated. Again, the question would come down to one of trade-off between the risks of launch failure and terrestrial contamination, versus the results of the object striking the Earth.

Mistaking impacts for nuclear detonations

Distinct from the considerations mentioned above is another NEO 'nuclear dimension' - the possibility of confusion between the effects of a meteoroid exploding in the air or impacting on the ground with those of a nuclear explosion. Meteor trails, and airbursts as incoming objects exploded in the atmosphere, have been detected from Earth-observing spacecraft. One in 1994 in the south Pacific has been widely quoted as leading to a nuclear alert in the USA

Seismic monitoring can detect underground nuclear explosions and is used to verify the Comprehensive Test Ban Treaty. The land impact of a 10m iron object, which occurs about once every decade, can be seismically similar to a 1 kiloton nuclear underground test. In 1995, a US Congressional committee investigated whether a 1993 incident in Australia, almost certainly such an impact event, could have been a terrorist nuclear test.

The risks from such mistaken identities are not currently well known, because of military security constraints.

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[22] The expectation would be that any such fragments which did approach the Earth would dissipate in its atmosphere.

[23] It is possible that some asteroids might be largely composed of valuable materials, such as iron and it has been suggested that in future they might be 'mined' for use on Earth.

[24] This assumes that the NEO defence system might be housed on a permanently Earth-orbiting station.

APPENDIX: THE SOLAR SYSTEM AND ITS MEMBERS – LARGE AND SMALL

Along with the nine major planets, a large population of comets and asteroids also orbits the Sun (**Figure 9**). Most comets (see later section) are thought to be contained in the 'Oort Cloud', lying in the furthest reaches of the Solar System, far beyond Pluto, at over 10,000 times the distance of the Earth from the Sun. The asteroids are concentrated in the Main Belt between the orbits of Jupiter and Mars (**Table 2**). Knowledge of the minor members of the solar system has become more complex as objects are found elsewhere in the solar system. Increased understanding has also weakened the formerly clear distinction between comets and asteroids.

TABLE 2 THE SOLAR SYSTEM

Object	Distance from Sun in AU* (semi-major axis of orbit)
Mercury	0.39
Venus	0.72
Earth-Moon distance	0.0026 (384,000 km)
Earth	1.00 (149,600,000 km)
Mars	1.52
Main Asteroid Belt	2.0-3.3
Ceres	2.77
Jupiter	5.20
Saturn	9.54
Uranus	19.18
Neptune	30.06
Edgeworth-Kuiper Belt	30 to 100
Pluto	39.44
Oort Cloud	10,000 to 100,000

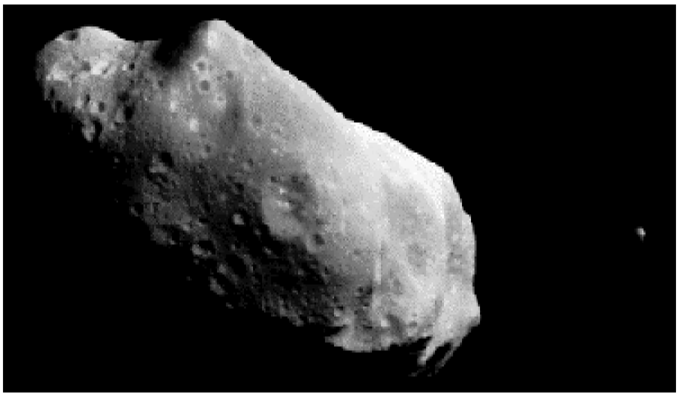
* One Astronomical Unit (AU) is the mean distance of the Earth from the Sun. The Earth's orbit, as with all the major planets, is elliptical. Apart from Pluto, however, all the planets' orbits are very nearly circular.

ASTEROIDS

Ceres was the first asteroid to be discovered, in 1801. Others were quickly detected and now over 10,000 have well-determined orbits. Many others have been found, only to be lost due to inaccuracies in estimates of their orbits, while new asteroids are still being discovered. The first asteroids discovered all have nearly circular orbits between the orbits of Mars and Jupiter, at a distance of about 3 AU from the Sun. This region is called the Main (asteroid) Belt (Table 2). In the surveys undertaken to find NEOs, most of the new objects detected are Main Belt asteroids (see **Figure 7**).

Ceres, about 940 km across[25], is the largest of the asteroids – and contains about one-third of the total mass in the asteroid belt. The two next largest have diameters of about 600 km but most asteroids are much smaller, down to a kilometre or so for the smallest directly-observed asteroid belt objects. Earth-based infrared detection and spacecraft observation show that belt material extends down to the micron scale.

FIGURE 7 ASTEROID IDA AND SATELLITE, DACTYL



Photograph by the Galileo spacecraft (NASA)

Ida is an irregularly shaped Main Belt asteroid, about 56x24x21km in size. It is the only asteroid known to have a satellite – Dactyl, about 1.6x1.4x1.2km – shown on the right in this photograph, which orbits Ida at distances of 90-100km. Dactyl was discovered by chance during the Galileo spacecraft's close approach to Ida, suggesting that other asteroids may also have satellites. Neither Ida nor Dactyl is a NEO.

Like the planets, asteroids reflect sunlight, but with considerably varying efficiencies. Some are very dark, reflecting under 5% of the sunlight. Their colour also varies, implying differences in their surface characteristics and composition. As more asteroids are examined, and more detailed observations are made, they display increasingly diverse forms and histories.

Asteroids can also be grouped by their orbits. These are not uniformly distributed within the asteroid belt, mainly because of the influence of Jupiter, by far the most massive of the planets. Its gravitational field causes gaps in the belt where there are few asteroids. Asteroids have a greater spread in both the eccentricity and the inclinations of their orbits to the ecliptic[26] than the major planets. There are also groups of asteroids with very similar orbits, probably the fragments of larger bodies that have collided, a process that is continuing.

Near Earth Asteroids (NEAs)

Not all asteroids orbit within the Main Belt. Several hundred are known to have orbits where their closest approach to the Sun (perihelion) lies close to or even within the Earth's orbit. These asteroids can be classified into groups determined by their orbital characteristics.

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[25] The Moon's diameter is 3,476 km.

[26] This is the plane of the Earth's orbit around the Sun.

'Apollos' are the main class of Earth (orbit) Crossing Asteroids (ECAs). 'Amors' cross the orbit of Mars but currently do not quite reach that of the Earth, while 'Atens' are a small group of ECAs with orbital periods less than a year, i.e. they orbit mainly closer to Sun than the Earth, making their detection particularly difficult.

The first of these asteroids was discovered in 1898 but as **Figure 8a** shows, the number detected has grown dramatically recently. **Figure 8b** and **Table 3** show the effects of Spaceguard survey activities on the discovery rate. The monthly rates of new discoveries now frequently exceed earlier annual and decadal rates.

An asteroid in any of these orbits will be subject to orbital perturbations caused by close passes to the inner planets[27] and is likely eventually to collide with one of them. This orbital evolution occurs over tens of thousands to hundreds of thousands of years. Current NEAs have not been in their present orbits from the earliest days of the solar system. and are continually refreshed by recruitment of new members. These are thought to be 'old' comets, (and the close similarity of NEA orbits with those of short period comets supports this supposition), as well as fragments from the asteroid belt.

TABLE 3 NUMBER OF NEW DISCOVERIES PER MONTH OF AMOR, APOLLO AND ATEN CLASS ASTEROIDS: JAN 1998 TO FEB. 1999, FROM VARIOUS SURVEYS

LINEAR: Lincoln Laboratory, US Air Force; **JPL/NEAT**: Joint Jet Propulsion Laboratory/USAF; **Spacewatch:** Arizona University, Kitt Peak Observatory; **LONEOS**: Lowell Observatory, Arizona

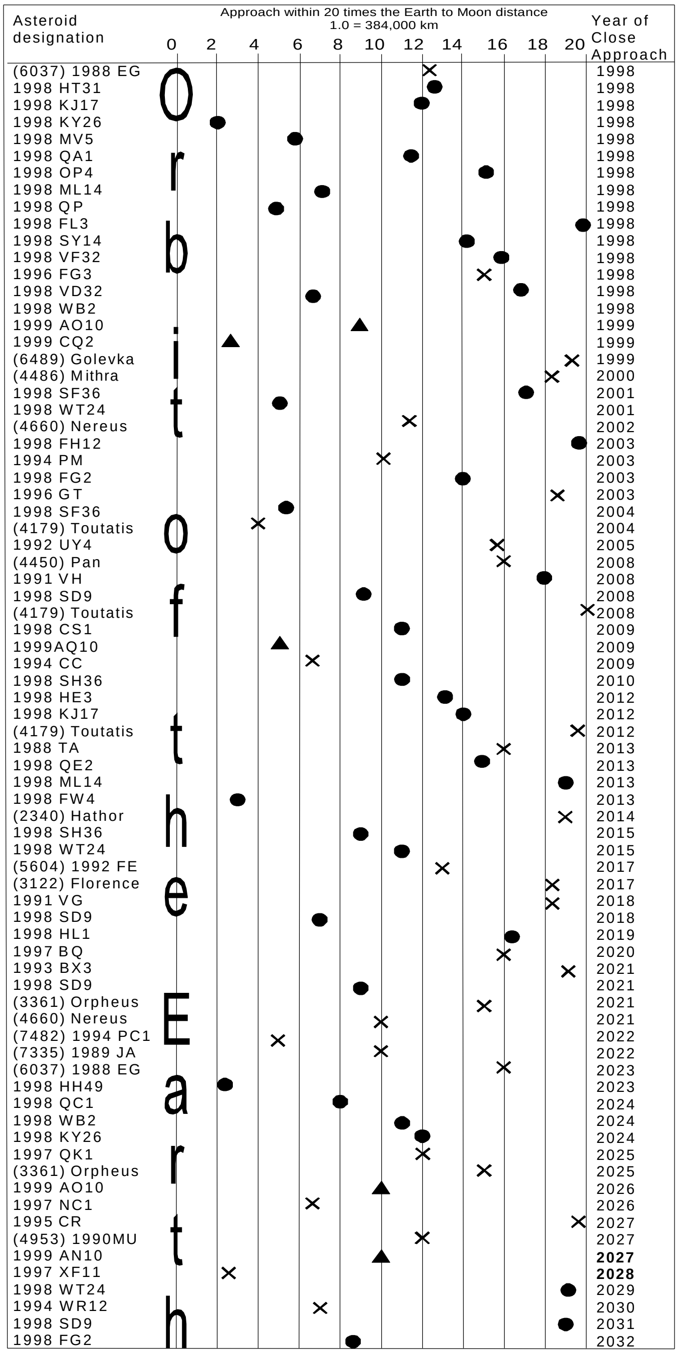
	LINEAR	JPL/NEAT	Spacewatch	LONEOS	Other
1998 Jan	0	5	3	0	0
Feb	0	1	2	0	2
Mar	13	1	3	0	3
Apr	9	2	7	0	1
May	12	0	3	0	0
Jun	10	0	1	1	1
Jul	1	2	3	0	0
Aug	16	0	3	2	0
Sep	27	0	4	2	1
Oct	8	0	2	1	1
Nov	19	0	4	1	4
Dec	20	0	1	0	2
1999 Jan	9	0	1	0	2
Feb	9	0	1	0	0
Total	**153**	**11**	**38**	**7**	**17**

Others:	**Number**
BAO Schmidt CCD Asteroid Program	2
Catalina Sky Survey	4
OCA-DLR Asteroid Survey	3
Individual observers	8

POTENTIALLY HAZARDOUS ASTEROIDS (PHAs)

'Potentially Hazardous Asteroids' (PHAs) are defined arbitrarily by the MPC as objects calculated possibly to pass the Earth at a distance of 0.05AU or less (about 20 times the Earth-Moon distance) and with an absolute magnitude (brightness) of 22.0 or less, (approximately

FIGURE 10 POTENTIALLY HAZARDOUS ASTEROIDS (PHAs) APPROACHING THE EARTH, 1998-2032



PHAs are defined in the text. The figure shows the distance and year of closest approach for PHAs having a close approach to the Earth within the time period 1998-2032. The triangles are 1999 discoveries, the crosses are 1998 discoveries, while the circles are pre-1998 discoveries. The nearer the symbols are to the left margin – the closer is the object's approach to the Earth.

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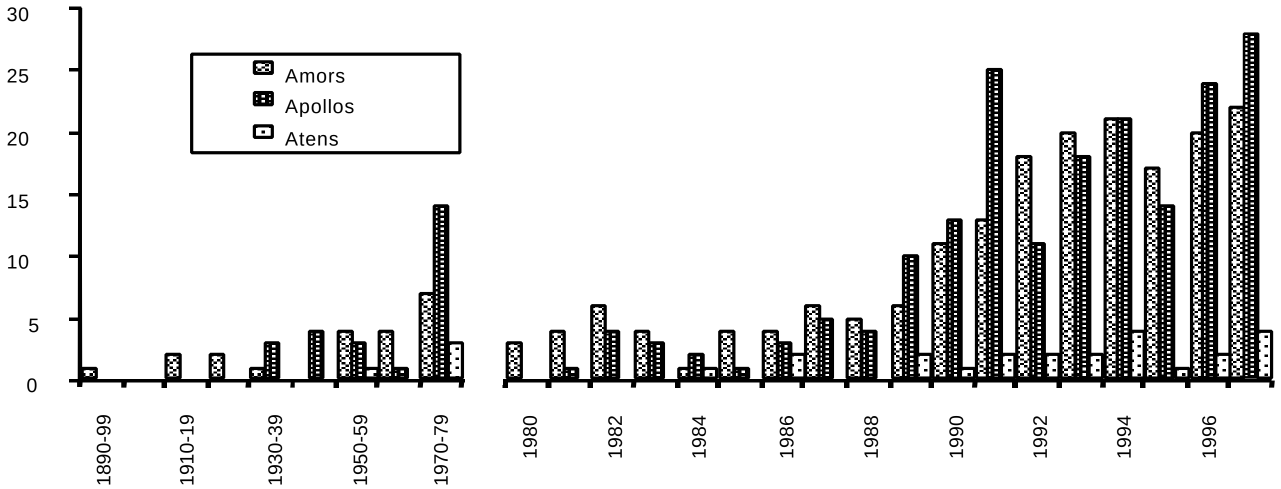
[27] i.e., Mars, the Earth, Venus or Mercury

FIGURE 8 DISCOVERY OF ECAs AND OTHER NEAR EARTH ASTEROIDS

Amors - asteroids with Mars crossing, but not Earth crossing, orbits:**Apollos** - asteroids with Earth crossing orbits and an orbital period greater than one year, **Atens** - asteroids with Earth crossing orbits and an orbital period less than one year

A) Number Discovered per Decade from 1890 To 1979 and then Number per Year 1980 to 1997



B) Number Discovered per Month from Jan. 1998 to Feb. 1999

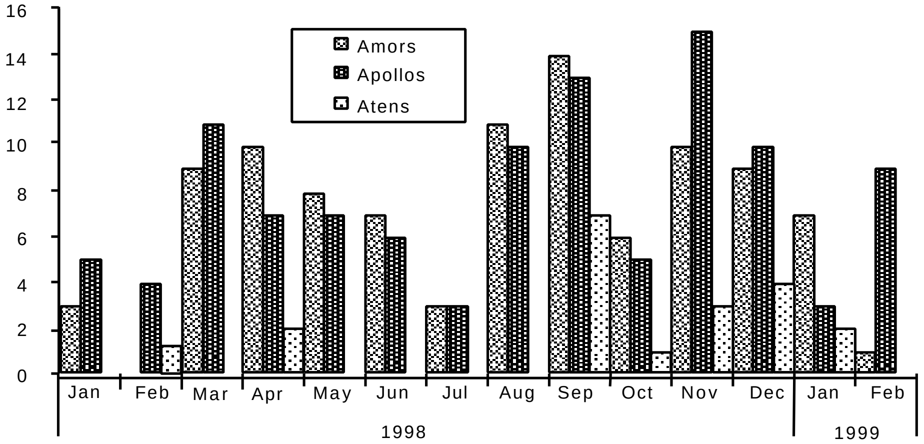
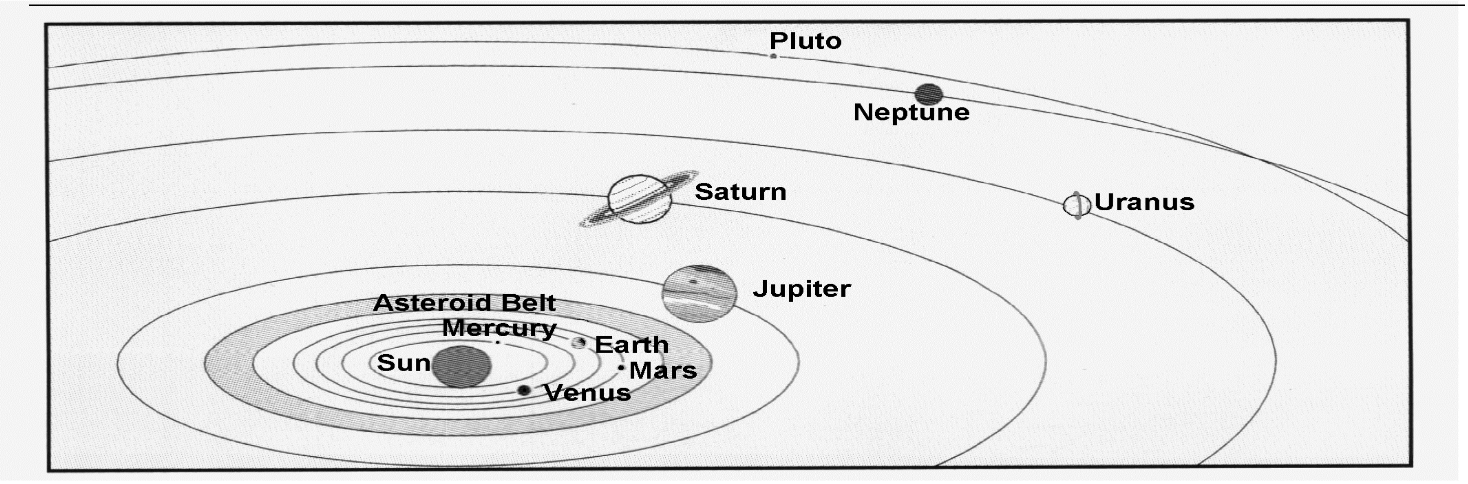


FIGURE 9 MAJOR MEMBERS OF THE SOLAR SYSTEM



Source: PPARC

Note that the sizes of the objects and their orbits are not to scale in this diagram. The orbit of Pluto, which many observers now believe to be simply a large Edgeworth-Kuiper Belt object, is highly eccentric, so that it occasionally lies closer to the Sun than Neptune, as it has done between 1979 and March 1999.

equating to over 150m in diameter[28]). **Figure 10** shows the list of such objects that have a closest approach in the next 32 years (as at 17/2/1999). The shapes on the figure indicate three groups of objects; those discovered before 1998; those discovered in 1998 and those discovered this year, up to 17/2/1999. At 15/4/1999, 170 PHAs had been designated.

The close approaches indicated by crosses – the PHAs discovered in 1998 – show how just one year's survey work has increased known numbers. As this work continues, these numbers, for both NEOs overall and PHAs, will also rise.

COMETS

Comets are usually thought of as bright objects in the night sky with visually spectacular tails. They are classified by their orbital period (the time they take to orbit the Sun on their highly elliptical orbits). Short period comets have orbital periods of less than 20 years, intermediate period comets periods of 20 to 200 years, while comets with orbital periods in excess of 200 years are long period comets.

Jupiter plays a major role in modifying the orbits of any objects moving inwards towards the sun, capturing them into the orbits typical of the short period comets. These have eccentric orbits, about 5AU at their furthest distance from the Sun. Jupiter may also act as a form of giant 'wicket keeper', capturing some straying objects from the outer part of the Solar System so that they do not threaten the inner reaches, including the Earth (see Figure 5).

Cometary nuclei are small. For example, that of the recent comet Hale-Bopp, one of the largest and brightest known, was only 40km across, while comet Halley's is only about 10 km wide (and irregular in shape). The tails that make comets so visible can extend for millions of kilometres. Tails are transient features, usually appearing only when a comet is within the orbit of Jupiter. As a comet's nucleus approaches the Sun and is heated more strongly, its ice starts to evaporate in jets of gas. Minute dust grains are also released. Solar radiation acting on these, and the ions and magnetic field streaming from the Sun interacting with the gases, create the tail, which points away from the Sun. Comet tails are very tenuous; the Earth passed unharmed (and unnoticed) through that of Halley's comet in 1910. Very close passages by the Earth can lead to meteor storms occurring.

Once gases start to be released from a cometary nucleus, it brightens considerably, making it easier to detect at a given distance than an asteroid, as telescopically it appears as a fuzzy object. The loss of material from the nucleus is not always evenly spread on the surface and directed jets of gas have sometimes been seen. These will have a small effect on the cometary nucleus's motion. The nucleus loses material, especially gases, each time it approaches the Sun. Eventually, after many close solar passes, a comet's volatiles are exhausted and only its rocky nucleus remains.

It is possible to calculate the furthest distance of a comet's orbit from the Sun (its aphelion). From this, the Dutch astronomer Jan Oort recognised that many comets have aphelia a great distance from the Sun. Comets also have orbits at all inclinations to the ecliptic. Oort proposed that there existed a spherical shell of comets lying far beyond the orbit of Pluto, at a significant fraction of the distance to the nearest star. This zone is called the 'Oort Cloud', and can be thought of as a 'storehouse' for long period comets, containing many billions of objects. Very occasionally the orbit of a comet in the Oort Cloud is perturbed and it may move inwards towards the main planets.

Shortly before Oort's work, Edgeworth had predicted the existence of a second major belt of comets, in an extended disc located just beyond orbit of Neptune (Table 2), a prediction reinforced in 1951 by the Dutch-US astronomer, Kuiper. In 1992, the first of these 'Edgeworth-Kuiper Belt' objects was found. Many of these icy objects are not in permanent residence in this part of the solar system. The planet Neptune's gravitational pull will either fling them outwards or inject them further into the solar system. Several objects, the so-called 'Centaurs', have been detected between the orbits of Neptune and Jupiter but these orbits are not stable.

The Edgeworth-Kuiper belt objects are ice-rock bodies, hundreds of kilometres across, similar to Pluto and the moons of Uranus and Neptune. The Main Belt asteroids resemble the outer moons of Jupiter and the Martian moons, all of which may be captured asteroids. This reflects the location of formation of these objects. The Main Belt asteroids formed approximately at their present location between the

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[28] Absolute magnitude is defined as the brightness of an object if it were to be at a distance of 2,062,650AU from the Earth. The *lower* the magnitude, the brighter (and generally, for NEOs, the larger) is the object.

orbits of Mars and Jupiter. At that distance from the Sun they would have been too warm to retain much water and ammonia ice. However the Edgeworth-Kuiper Belt objects are far enough from the Sun to have retained these light volatiles. Probably the only significant distinction that can be made between an Edgeworth-Kuiper Belt object and a cometary nucleus is based on their differing orbital characteristics.

METEORS, METEOR SHOWERS AND FIREBALLS

On a dark night, away from city lights, it is a common sight to see a brief streak of light in the sky - a meteor (shooting star), caused by the destruction of minute fragments of material from interplanetary space from frictional heating in the Earth's atmosphere. Although usually visible only at night, this rain of interplanetary grains continues all the time – 50,000 tonnes entering the atmosphere annually. Exceptionally bright meteoric objects may be seen even in daylight.

The sighting of a meteor is not always just a random, isolated event. At some times of the year hundreds of meteors an hour will enter the atmosphere, and those seen by an observer will all appear to come from a single point in the sky (a 'radiant'). Such meteor showers are predictable, within certain limitations of accuracy. An example is the Leonids, with a radiant in the constellation Leo, which have expected rates of several tens of meteors per hour every 17th November[29]. This shower is one of several that occur when the Earth crosses the orbit of a known comet (Comet Temple-Tuttle in the case of the Leonids).

At times what is seen in the night sky is a fireball (sometimes called a 'bolide') – a short-lived broad track of light, which can be much brighter than the full Moon, sometimes accompanied by a sonic boom or thunder-like sound. The incoming object usually fragments in the air as it breaks up into smaller pieces and molten droplets trail from its surface, spreading back along its track. This reduces the size of the original object, which can melt away and fragment, sometimes explosively, in the atmosphere, so that no sizeable remnant, if any, reaches the ground. A fireball's light is caused mainly by the heated atmosphere, not by its molten surface, which is only a small fraction of the size of the luminous region.

In a few cases, sufficient observations of the track of a fireball have been recorded to derive an orbit for the incoming object. In all cases the orbit has had an aphelion in the asteroid belt. These objects therefore have orbits similar to some ECAs.

METEORITES

Meteorites are the remnants of extra-terrestrial material that reach the ground. They often fall in clusters if the incoming object fragments in the air; pieces of rock may be scattered over several square kilometres. About six meteorite falls per year result in the collection of material associated with each fall. Many meteorites, however, fall into the ocean. Also, as falls are scattered over a wide area, the meteoritic material may not be recognisably distinct from the surface rocks.

On the other hand, demonstrably meteoritic rocks that are not linked to any observed fall may be found on the earth's surface. In some parts of the world where surface conditions favour their preservation (such as Antarctica and the Nullarbor Plain in Australia) these 'finds' may have fallen many thousands of years ago.

The rocks of meteorites have a wide range of properties and composition. They can be grouped into five broad categories, and many finer divisions depending on their detailed composition and mineralogy. The most basic division is by the proportion of metal the meteorite contains, and also the presence or absence of 'chondrules' – small rounded objects, some large enough to be visible to the naked eye. Meteorites collected on the Earth can be related to various classes of asteroid (using reflectivity and spectroscopy) as well as to terrestrial and lunar rocks (by chemical analysis).

The most common objects, the 'stones' -- also called 'chondrites' -- are similar in composition to the crust and mantle of the inner planets. They account for about 80% of the finds and an even larger percentage of falls. They show evidence of being a conglom--eration of lumps of material which have welded together. Some meteorites contain chemical elements in similar proportion to the Sun, (except for the gases). These are the 'carbonaceous chondrites'. They can be regarded as the most primitive of the meteorites as they have been less altered since their formation than the other types. Most of the falls and finds that are not 'stones' are 'irons'. These make up nearly 20% of finds, as they are noticeably massive rocks for their size and very metal-rich. Another group of meteorites – the 'stony-irons' – is composed of mixtures of iron-rich and stony material, The rare 'achondrites' have no

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[29] A particularly intense shower may occur in November 1999.

chondrules, and are similar to volcanic basalt, having been melted at some time. They are believed to originate from the Moon, Mars and the Main Belt asteroid Vesta (**figure 11**).

FIGURE 11 IMPACT SCAR ON THE ASTEROID VESTA

Photograph: NASA – Hubble Space Telescope, 1997

Vesta is the third largest asteroid, at about 500km across. Its impact history is among the most remarkable in the Solar System. It has been struck by a 30 km object, leaving a crater structure over 400 km across, with a central peak over 12 km high. Although not the largest crater in the Solar System, it is easily the largest relative to the size of the impacted object. An impact any larger would probably have caused total disintegration of the asteroid. At least 30 other asteroids are believed to be the remnants of this collision, which is also responsible for about 6% of the meteorites found on the Earth.

The irons and the mixed stony-irons are all assumed to originate from several larger objects. These must have been large enough to have molten interiors, so that their component materials were separated. For example, any iron would form the core of such an object, together with other associated elements such as iridium and platinum. On the Earth, these elements are present in the crust at very low levels compared with their proportionate abundance in many meteorites, because of their selective concentration in the Earth's iron core. The measurable concentrations of iridium in geological deposits associated with the Chicxulub crater led to the conclusion that the boundary between the Cretaceous and Tertiary periods is linked to an impact event.

The minimum size for an object to reach the ground will depend on its composition– smaller, iron, objects being stronger than larger, stony, ones. Thus, for any given size, although rarer, those composed of stronger materials will be the objects more likely to do damage.

FURTHER INFORMATION

There is a considerable amount of information available on NEOs and the Solar System more generally on the Web. Particularly useful sites are:

Spaceguard Foundation
spaceguard.ias.rm.cnr.it/SGF

Spaceguard UK
dspace.dial.pipex.com/town/terrace/fr77/index.htm

Reports and Spaceguard News
impact.arc.nasa.gov

Hansard Report of House of Commons Adjournment Debate, 3rd March, 1999
pubs1.tso.parliament.uk/pa/cm199899/cmhansrd/cm990303/debtext/90303-53.htm#90303-53_head1

US Congressional Science Committee Hearings
www.house.gov/science/hearing.htm#Space_and_Aeronautics

Solar System Information
star.arm.ac.uk
www.rog.nmm.ac.uk/leaflets/index.html
ast.star.rl.ac.uk/forum
helio.estec.esa.nl/
sse.jpl.nasa.gov/

NEOs and Meteorites
echo.jpl.nasa.gov/links.html
seds.lpl.arizona.edu/nineplanets/nineplanets/meteorites.html
www.meteor.co.nz/may97_2.html

Impacts on Earth
gdcinfo.agg.nrcan.gc.ca/crater/paper/cratering_e.html
gdcinfo.agg.emr.ca/toc.html?/cgi-bin/crater/crater_table

The 'Tunguska Event'
www.galisteo.com/scripts/tngscript/default.prl
bohp03.bo.infn.it/tunguska96/

Tsunami
www1.tpgi.com.au/users/tps-seti/spacegd7.html

Deflection/Fragmentation Techniques
www.llnl.gov/planetary/