Jupiter: friend or foe?

Jonti Horner and Barrie W Jones re-examine the role of giant planets in the evolution of life – specifically, whether Jupiter has in fact shielded Earth from excessive extraterrestrial bombardment.

Abstract

The idea that Jupiter has shielded the Earth from potentially catastrophic impacts has long permeated the public and scientific mind. But has it shielded us? We are carrying out the first detailed examination of the degree of shielding provided by Jupiter and have obtained some surprising results. Rather than Jupiter acting as a defensive presence, we found that it actually makes little difference – but if Jupiter were significantly smaller, the impact rate experienced by the Earth would be considerably enhanced. Indeed, it seems that a giant planet in the outer reaches of a planetary system can actually pose a threat to the habitability of terrestrial worlds closer to the system's parent star.

For decades, writers of science fiction have toyed with the question of life elsewhere. In the public consciousness, olive-skinned alien maidens dance with brave Star-fleet captains, small green creatures offer cryptic advice, and the space between the stars is packed with sleek, fast moving vessels.

The question of life beyond Earth has fascinated people since we first looked at the sky. As science has evolved, and our knowledge of the universe improved, the question is still asked: could there be creatures out there, looking at the night sky, and wondering whether we exist?

In the past 15 years, discoveries have cast the question of extraterrestrial life in a whole new light. The first planets have been discovered around distant stars. Every year, the number rises (currently, around 300 such planets are known) and we are creeping closer to being able to detect Earth-like worlds at distances so great that they are beyond our imagination. The light we observe from Epsilon Eridani, for example, the star at the centre of one of the nearest known planetary systems, has travelled for 10.5 years, covering a distance of 99.3 million million kilometres. Across these and even greater distances, we could be observing Earth-like planets within 20 years, circling their stars at a distance such that their surfaces are habitable.

Given that we are now on the doorstep of such immense discoveries, the time has come to study – in detail – what it takes to create a habitable planet. At the Open University we are looking into one particular determinant of habitability, namely the extent to which giant planets in a planetary system protect habitable planets from excessive bombardment that would stifle evolution, or even sterilize the planet. Though we've only been studying the problem for around a year, it has already thrown up some fascinating new results. But do impacts really matter?

1: The Barringer Crater in Arizona. It is some 1.2 km across, around 170 m deep, and was excavated about 50 000 years ago by a lump of nickel-iron about 50 m across. (USGS)

A menace not to be ignored

If you take a trip to Arizona, one of the most spectacular places to visit is the Barringer Crater, more commonly known as Meteor Crater (figure 1). This large, sharply defined hole in the ground is about 1.2 km across, around 170 m deep, and surrounded by a rim that rises almost 50 m above the surrounding desert. Although nowadays it is well accepted that this is the scar of an ancient impact, left when a lump of nickel-iron about 50 m across slammed into the desert around 50 000 years ago at several kilometres per second, it wasn't until the early 1900s that this idea was even mooted, by Daniel Barringer. Before this, the crater and others like it worldwide were considered artefacts of volcanic activity, and any suggestion that they could be anything else was scorned. That things could crash into the Earth and dig out these huge holes was simply unbelievable.

Despite the fact that Meteor Crater is one of the best preserved impact craters on the surface of the Earth, and that the weight of the argument for its meteoritic origin built through the 20th century, its origin was not proven beyond doubt until the early 1960s. So the study of impacts on the Earth is a remarkably young science – particularly given the strong evidence for the many impacts over geological timescales. The surface of the Moon, free from the weathering, plate movements and oceans that rapidly erode the great majority of impact features on the Earth, shows craters upon craters, large craters, small craters, old craters and new craters.

The idea that impacts could threaten the biosphere has also been slow to gain acceptance. The suggested link between the extinction of much life on the Earth 65 million years ago, including the dinosaurs, and a huge impact structure buried beneath the rocks off the northern Yucatan coast of Mexico, has done much to establish the impact threat among the general public. The 1908 devastation in Tunguska (see box "The greatest impact of the 20th century") shows us that impacts pose a risk even today. The number of near-Earth asteroids and comets discovered in recent years underline the point. Impacts pose a very real threat to life on the Earth, and surveys are now active across the planet in an attempt to catalogue every potentially hazardous object, in search of the next source of "death from above".

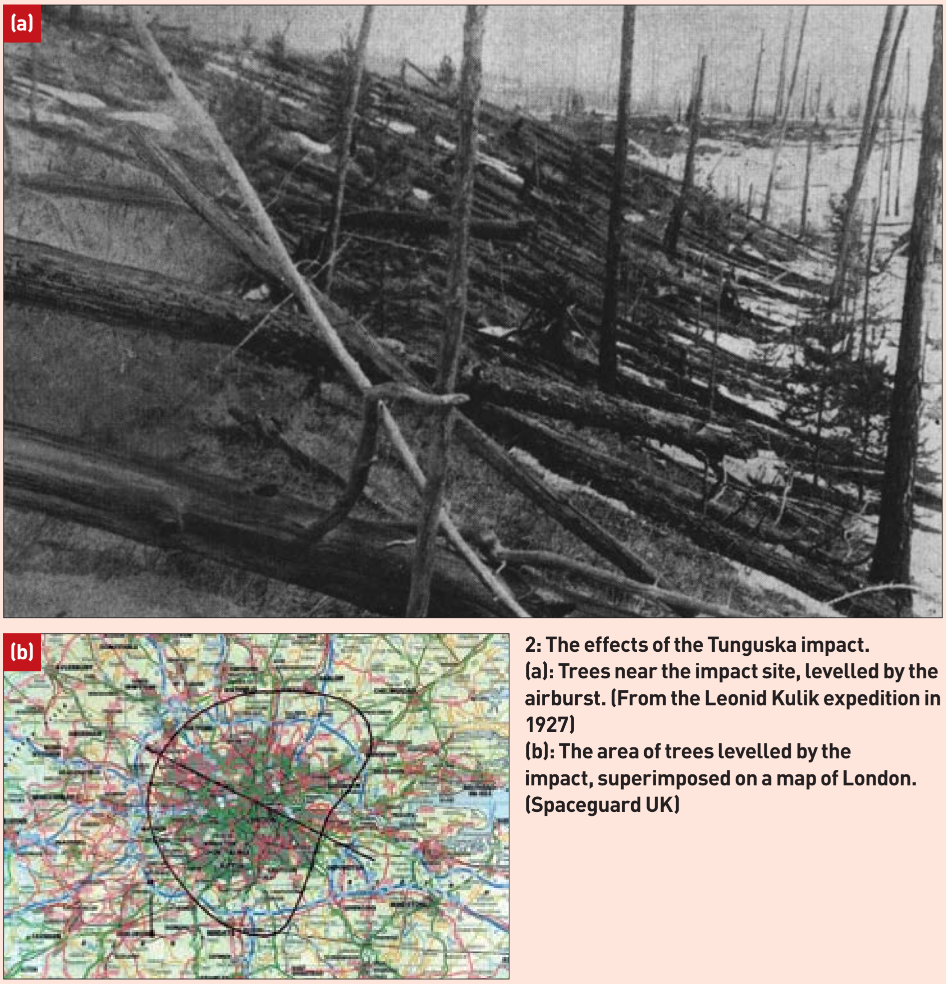
It is now accepted that collisions can threaten life on the Earth. Current thinking suggests that an object 1 km across would do enough damage to kill a quarter of the world's human population. Such impacts are hypothesized to occur approximately once every 300 000 years. Clearly, the more often such impacts (and their larger brethren) happen, the harder it will be for life to become established, and for it to develop and flourish. On the other hand, though, if impacts are too scarce, perhaps evolution would stagnate. It is clear, too, that all these considerations are equally applicable in the case of exoplanetary systems.

The greatest impact of the 20th century: Tunguska

In 1908, in the depths of Siberia, a giant explosion high in the atmosphere levelled trees over an area roughly equal to that of greater London. The flames from the event were so widespread that it was possible to read a newspaper at midnight, in the UK, for several days afterwards. Fortunately, the explosion happened in an uninhabited part of the world – doubtless a few unfortunate reindeer were killed, but otherwise, we got off rather lightly. It has been suggested that had the event happened just a few hours later, the city of St Petersburg would have been destroyed.

It is thought that the object that detonated high above Tunguska was a fragment of a comet or an asteroid, significantly smaller than that which created the Barringer crater. In fact, it seems likely that impacts on this scale occur at a rate somewhere between once every century, and once every millennium.

Currently, it is highly unlikely that an object as small as the Tunguska impactor would be detected *en route* to the Earth, and so such an event could happen again, at any time, without warning. The odds of it happening this year, within damaging range of the reader, are almost vanishingly small, but, eventually, it will happen.



2: The effects of the Tunguska impact.
(a): Trees near the impact site, levelled by the airburst. (From the Leonid Kulik expedition in 1927)
(b): The area of trees levelled by the impact, superimposed on a map of London. (Spaceguard UK)

Where do all these threatening objects come from? In our solar system, at least, there are two sources of potential impactors: the comets and the asteroids.

Comets

Bright comets have long been considered things of beauty, inspiring fear and awe. A truly spectacular comet, such as Hale–Bopp in 1997, or McNaught in 2007 (figure 4), is something that will be observed and noted the world over, and in ancient days these brilliant yet fleeting celestial visitors were viewed as harbingers of doom and messengers of the gods.

We now know that comets are ice-rich bodies, typically several kilometres across, that come from two main reservoirs – cold storage regions that contain trillions of such objects. The great majority of short-period comets we see (such as 17P/Holmes) started their life in a disc of debris just beyond the orbit of Neptune, which includes the Edgeworth–Kuiper belt (e.g. Jewitt 1999). Other than Pluto, the first Edgeworth–Kuiper belt object was found only in 1992, but we already know a few hundred of these bodies and that's just the tip of the iceberg. The objects in the Edgeworth–Kuiper belt move on orbits that are highly stable – after all, they've survived out there for the age of the solar system. However, occasionally a couple of objects in this region will have a close approach with each other, even collide, sending material onto new paths in the outer solar system. Some of this debris acquires orbits that cross that of Neptune, and the giant planet feeds them into the outer solar system, where they become "Centaurs". The Centaurs (the most famous of which is the 200 km diameter object Chiron) are the direct parent population of the short-period comets, and so we have a steady "hand me down" process, feeding material from the Edgeworth–Kuiper belt, to the Centaurs, and from there into the inner solar system, where they become potential Earth impactors.

Other comets, such as McNaught and Hale–Bopp, have their origin much further from the Sun, in the Oort cloud (e.g. Weissman 1990). The cloud, which stretches halfway to the nearest star (about 100 000 times the distance from the Earth to the Sun) probably contains many trillions of comets, most of which will orbit far from the Sun indefinitely. A select few receive nudges from passing stars or the tidal pull of our galaxy, and swing inwards towards the Sun. As they swing through the inner solar system, some of them (such as comet Hyakutake in 1997 or comet IRAS–Iraki–Alcock in 1983) approach the Earth closely before swinging back out into the depths of space. These comets from the Oort cloud pose a threat to the Earth – if we wait long enough, one will come too close and crash into us.

The great majority of Oort cloud comets pass through the inner solar system just once and are then ejected, never to return – but occasionally, an encounter with a planet can swing them onto ever shorter period orbits, until, for a comet like Hale–Bopp, their millions-of-years orbital period is reduced to a few millennia, or even shorter.

The comets, however, aren't thought to pose the main impact threat to the Earth – that distinction lies with a group of bodies called near-Earth asteroids (NEAs for short).

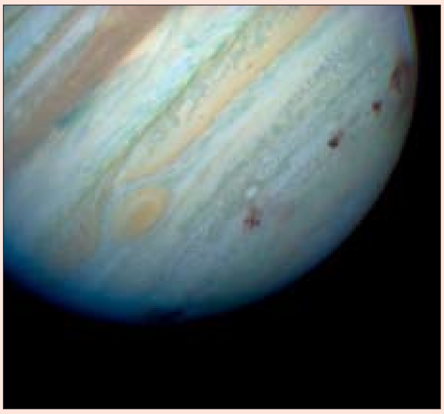
Asteroids

The history of the asteroids isn't as long or detailed as that of the comets – in fact, the first one wasn't discovered until 1801. This is Ceres and, at nearly 1000 km across, is by far the largest. Since then, however, more than 300 000 of

Impact! Comet D/Shoemaker-Levy 9

1994 saw the most recent great impact in the solar system. In that year, the many fragments of comet D/Shoemaker-Levy 9 ploughed into Jupiter. Although the impacts took place on the far side of the planet, and so could not be directly observed from the Earth, their effects were clearly visible – and far greater than anyone had expected. Scars the size of our planet were visible on the face of Jupiter for many months after the event, and the huge impact plumes generated by the collisions were observed by the Galileo spacecraft. The plumes were so vast that they were observed rising above the edge of the planet, over the hidden impact site, by the Hubble Space Telescope.

The history of the comet is now fairly well understood. At some point in the late 1960s or 1970s, it was captured into orbit around Jupiter from a path most likely to have been similar to those of the short-period comets. Until its discovery in 1993, it swung around the planet unnoticed with a period of around two years, its orbit flexing under the influence of the Sun. At its penultimate perijove (closest approach to Jupiter), it came so close to the planet that the tide raised by Jupiter tore the comet into a vast number of pieces, more than 20 of which were large enough to be observed from the Earth. Over the comet's final orbit around the planet, these pieces slowly spread into a necklace-like chain of nuclei, which proceeded to slam into the planet over a week in July 1994.


3: The scars left by the impacts of Shoemaker-Levy 9, as imaged by the Hubble Space Telescope. (STScI)

The impact provided a wealth of information on the nature of impacts, allowing modellers to better constrain their understanding of the effect of these catastrophes. It also taught us a great deal about the atmosphere of Jupiter, and raised the profile of the impact hazard in the general public. One of us (JAH) remembers helping show the impact scars to large crowds of people at open nights at the West Yorkshire Astronomical Society – the interest among the general public was immense.

these rocky bodies have been found, and they're now being discovered at a rate of more than 5000 per month.

Most asteroids pose no threat to life on the Earth, moving between the orbits of Mars and Jupiter in the asteroid belt. Their orbits are stable over billion-year timescales – they move sufficiently far from the domineering influence of Jupiter that they would never, ordinarily, be perturbed onto paths that come anywhere near the Earth. However, every now and then, two will run into one another. The debris from such collisions is thrown far and wide, and can stray into orbits that are far less stable than those of the two colliding bodies. These fragments, ranging in size from grains of dust to rocks tens of kilometres across, fall under the sway of Jupiter and are swung onto ever-more perilous orbits until they reach the inner solar system. Once there, these new NEAs continue to be pushed around until they either fall into the Sun, hit a planet, or come close enough to one of the massive worlds to be flung out of harm's way. This means, in effect, that the Earth falls victim to a continual rain of material from the asteroid belt – the debris of ancient collisions. Given that the largest NEA that we know of is 32 km or so in diameter (Ganymed), it is clear that such objects pose a real threat to life on the Earth.

The immediacy of this threat is occasionally highlighted in the popular press – sometimes a new NEA is discovered and, until the orbit is determined with sufficient accurately, it appears that there is a small chance that the object will collide with us in the near future. When this happens, there is often a large amount of understandable excitement, which generally lasts until new observations confirm that the object will definitely miss the Earth. The day will come, however, when the observations will show that the object *will* hit – it is just a matter of time.

So, we have three populations of objects that can come close enough to threaten the Earth: comets from the Oort cloud, comets from the Edgeworth–Kuiper belt, and the NEAs. How does the presence of Jupiter influence the threat these objects pose?

Jupiter: friend or foe?

This is the particular area of our research at the Open University. For many years it has been accepted that, without the planet Jupiter, the impact rate on the Earth would have been far higher, and therefore that large animals (including us) would never have evolved. The idea that a giant planet is required beyond the orbit of a terrestrial one, in order that that planet be habitable, is well entrenched in the astronomical community (see, for example, Ward and Brownlee 2000), and is a staple of popular science when addressing the impact threat. The truth of the situation is, however, not so clear cut.

It is hard to find the origins of the "Jupiter as shield" theory. Looking through astronomical literature, only one paper has ever reported a detailed study of Jupiter's effect on the impact rate: the work of George Wetherill (1994), who looked at the threat posed by comets swinging Earthwards from the Oort cloud. The roots of the idea, however, go back significantly further in time. People learning about astronomy in the late 1980s and early 1990s came across the idea that Jupiter protects us from impacts – the urls given in "References" at the end give examples of the pervasiveness of this idea. One possibility is that the idea comes from the study of impacts on the Earth in the 1950s and 60s. Back then, only a couple of NEAs were known, together with a relatively small number of short-period comets. The Oort cloud comets were regarded as being the main threat to the Earth and, for these objects, Jupiter does seem to act as a shield. In fact, as pointed out above, the majority of comets from the Oort cloud swing past the Sun just once, before being lost forever to interstellar space. The cause of their ejection? Jupiter. A comet fresh from the Oort cloud is so loosely bound to the solar system that it doesn't have to come very near Jupiter for the effect of the giant planet's gravity to provide enough of a nudge for it to become unbound, never to return.

However, the situation has changed. The number of short-period comets and NEAs that have been found by automated surveys (such as LINEAR and NEAT in the last few years) have revolutionized our understanding of the threat posed to our planet. Now the NEAs are regarded as the greatest impact risk, with the Oort cloud comets relegated to a much lower level of significance. It is clearly time to revisit the idea of "Jupiter – the shield", in light of this new information, and to study the effect it has on all three populations of potential impactors.

The main way that Jupiter could shield the Earth from impacts is by throwing objects out of our solar system, preventing them encountering our planet. In addition, Jupiter is likely to be the most impacted body in the solar system; while an object like comet D/Shoemaker-Levy 9 might hit the Earth every few million years, or tens of millions of years, Jupiter is hit far more

Comets

Bright comets have been recorded throughout our history, inspiring both hope and despair. As an example, Diodorus Siculus, talking about the great comet of 371 BC, wrote:

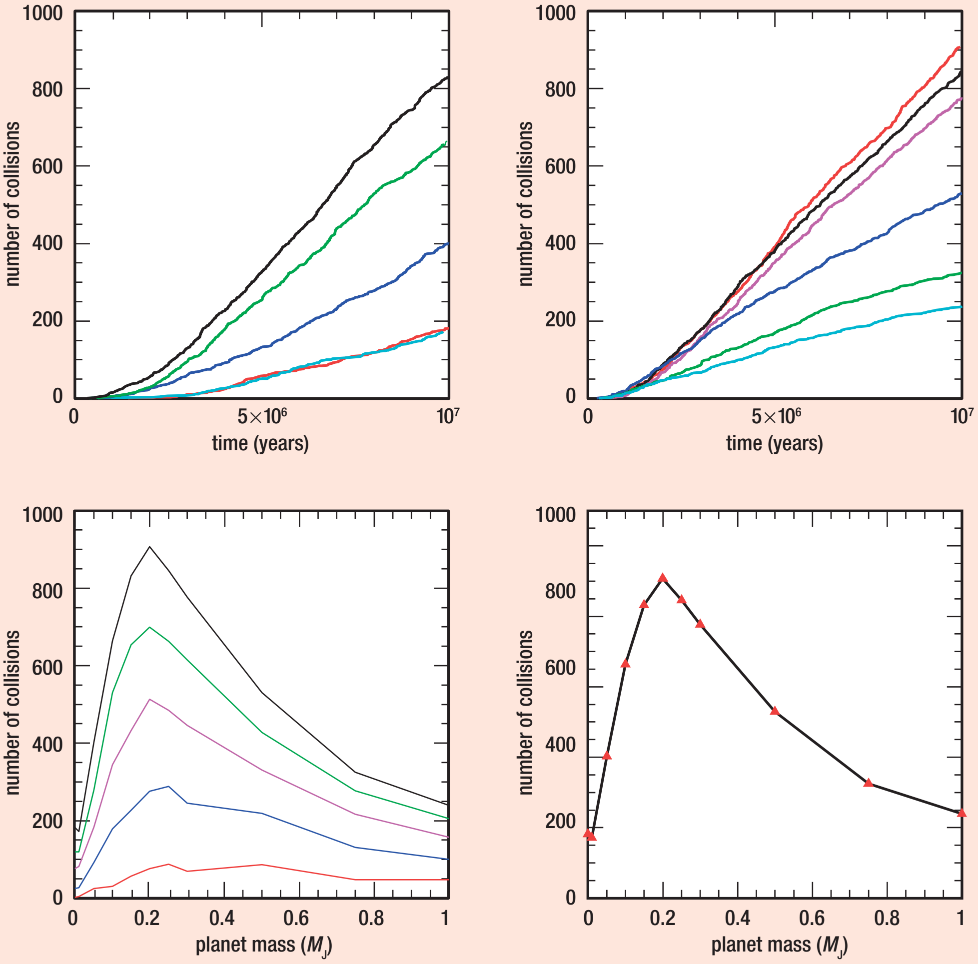
> *"There was seen in the heavens during the course of many nights a great blazing torch which was named from its shape a flaming beam…"*
>
> *"Some of the students of nature ascribed the origin of the torch to natural causes, voicing the opinion that such apparitions occur of necessity at appointed times, and that in these matters the Chaldeans in Babylon and the other astrologers succeed in making accurate prophecies…"*
>
> *"At any rate this torch had such brilliancy, they report, and its light such strength that it cast shadows on the earth similar to those cast by the moon."*

(Text taken from Gary Kronk's *Cometography*, vol. 1.)

When comets are observed we can calculate their orbit, and once we know that, it is possible to work out where and when they should have been seen at previous apparitions. By looking through ancient records, it is possible to tie these observations to a given comet. This helps scientists to refine the orbit of the comet, allowing them to search still further back in history. In this way, comet 1P/Halley has now been traced back to an apparition in 239 BC, and still more ancient observations are suspected going back to 2467 BC!

Nowadays, an increasing number of "periodical" comets are known – comets with orbital periods up to a couple of hundred years. As well as these short-period comets, we also see long-period comets – objects on orbits that take thousands or even millions of years to complete. These are also known as the Oort cloud comets, referring to their genesis in a great cloud containing trillions of cometary nuclei, stretching halfway to the nearest star.

4 (a): Comet Hale–Bopp, which passed through the inner solar system in 1997. (Francisco Diego and University College London)
(b): Comet McNaught, which passed through the inner solar system and was best seen from Earth in January 2007. This image shows the Chiro Observatory (Australia) in the foreground. (Akira Fujii/David Malin Images)



5: The upper two panels show the impact rate on the Earth as a function of time for 11 different masses of Jupiter. Top left: The collision rate for the cases where the Jupiter mass equals 0.0 M_J (red), 0.01 M_J (cyan), 0.05 M_J (blue), 0.10 M_J (green) and 0.15 M_J (black). Top right: The results for 0.20 M_J (red), 0.25 M_J (black), 0.30 M_J (purple), 0.50 M_J (blue), 0.75 M_J (green), and 1.00 M_J (cyan). Lower left: The number of impacts at five time slices, as a function of jovian mass. Red line after 2 Myr, blue line 4 Myr, purple line 6 Myr, green line 8 Myr, black line 10 Myr. Lower right: Again, the total number of impacts occurring by the end of 10 Myr as a function of jovian mass, with triangles marking the individual data points.

often – perhaps closer to once every millennium (figure 3). So, Jupiter shields by sweeping debris up, either by direct physical contact, or, far more frequently, through close encounters that throw objects out of our solar system. The great majority of comets will eventually be ejected in this latter way, Oort cloud comets and short-period comets alike.

The flip side of the coin is also true, however – for an object to threaten the Earth, it first has to have an Earth-crossing orbit. Were Jupiter absent, there would be far fewer short-period comets, and it is likely that the asteroid belt would be far less heavily stirred, though it is also true that, without Jupiter, the asteroid belt would no doubt look very different! Every encounter between a small body and Jupiter is random – it throws objects inwards as well as outwards, and can just as easily place objects onto an Earth-crossing orbit as it can remove them from these orbits. Therefore, it is clear that at least some of the objects that hit the Earth would not have done so, had Jupiter not played a role.

Whether Jupiter acts as a friend or a foe comes down to the balance between the two effects discussed above – does Jupiter provide more of a shielding effect, or is the contribution to the terrestrial impact flux so enhanced by the objects it throws our way that this outweighs its defensive work? In order to examine this balance, we are in the process of a series of detailed integrations, following the behaviour of hundreds of thousands of potential impactors in a range of theoretical solar systems. Given that there are three reservoirs of potentially hazardous objects (the Oort Cloud, the Edgeworth–Kuiper belt, and the asteroid belt), our study will be looking at each of these reservoirs in turn.

Testing the Centaurs

In the past, one of us (JAH) has worked on the Centaurs, the daughter population of the Edgeworth–Kuiper belt and parents of the short-period comets. Therefore, this seemed the most sensible place to start our study, even though it is likely that, of our three reservoirs, these objects pose a lower long-term threat to the Earth than the asteroids or Oort cloud comets. To study the jovian influence on the impact rate from objects coming inwards from the Centaur region, we set up large-scale simulations of the solar system. We set up 11 different versions of our planetary system. In each system we had the planets Earth, Jupiter, Saturn, Uranus and Neptune. These planets all started in the same place in each run and through all our simulations Saturn, Uranus and Neptune had the same mass as they do in our current system. The Earth in our simulations was artificially inflated – we gave it a radius of approximately a million kilometres, effectively enlarging the dartboard at which Jupiter could direct missiles. This was done to improve the impact statistics. In each run, we gave Jupiter a different mass, ranging between a system with no Jupiter (mass = 0), and a system with a Jupiter identical to our own.

To provide our population of potential impactors, we searched through the list of objects that have been discovered in the outer solar system. We took those that had already left the stable Edgeworth–Kuiper belt, but still moved much further from the Sun than the part of our solar system that is under the direct influence of Jupiter. This gave us 105 objects. Once Pluto had been removed from our sample, we made just over 1000 copies of each body, varying orbital characteristics slightly so that we ended up with a sample of some 107 000 discrete bodies, all lying on orbits beyond the orbit of Uranus.

These were then tracked in each of the test systems, created through the modifications to Jupiter's mass, for a period of 10 million years. If they hit a planet, the Sun, or were ejected from the solar system, they were removed from the simulation and the software noted their fate. By the completion of our runs, we had a record of the ejection rate and impact rate over the10 million-year period for each set-up. The results were more than a little surprising. Were Jupiter solely a shielding influence, then

Planetary pinball: the case of comet D/1770 L1 (Lexell)

In June 1770, Charles Messier discovered a new comet. The comet's brightness grew rapidly and it became easily visible to the naked eye. It moved unusually quickly across the sky, before fading away. It had passed just 0.0146 AU from the Earth, the closest cometary encounter in recorded history. Calculating the orbit of the comet from how it moved at that encounter, we now know it was moving on a six-year orbit at the time. Why hadn't it been discovered earlier? The answer comes down to planetary pinball – the mechanism by which objects on non-threatening orbits are moved onto different paths that could approach the Earth, and the way that threatening objects are often dispatched to safer regions.

Before around 1767, Lexell was moving on an orbit with perihelion (its closest approach to the Sun) position out near the orbit of Jupiter. That year, though, as the comet swung inward, it encountered Jupiter, which threw it onto its new path, with a six-year orbital period, and a very close approach to the Earth. Twelve years later, when Jupiter had completed a single orbit, and the comet two, the objects approached one another again, and this time the giant planet threw the comet into the cold, dark depths of the outer solar system.

Exactly where the comet is now, nobody knows – the observations made by astronomers in 1770 were not detailed enough for us to determine its orbit accurately enough to be certain, but the most likely scenario is that it is making its way out of our solar system, *en route* to a life wandering the galaxy.

In one 12-year period, Jupiter acted as both friend *and* foe with respect to this comet–first sending it our way, before removing it from its threatening path.

one would expect that, as its mass increases, the impact rate upon the Earth would fall off. Similarly, if Jupiter were solely a threat, then as the mass increased, so would the impact rate at the Earth.

Our results are shown in figure 5 and it is immediately apparent that neither of these scenarios is the case. As the mass of Jupiter is increased, the impact rate from objects moving inwards from the Edgeworth–Kuiper belt first rises to a peak, then falls away again. The end result is that a Jupiter like our own (one Jupiter mass) provides an almost equivalent amount of shielding to no Jupiter at all! More importantly, were our Jupiter smaller, then the impact rate from this Centaur-derived population of objects would have been *higher* than in either extreme case. In the worst case, with a Jupiter around 0.2 times the mass of our planet, the impact rate would have been significantly higher than at either extreme!

Why is this? Our qualitative reasoning is as follows. When there is no Jupiter, then very few objects acquire Earth-crossing orbits (Saturn is much less effective than Jupiter), and so the impact rate is particularly low. As the mass of Jupiter increases, the efficiency with which it places objects onto Earth-crossing orbits also increases, and so the impact rate rises. Eventually, though, as the mass increases still further, Jupiter becomes ever more efficient at ejecting the particles from the solar system entirely, and removes them from Earth-crossing orbits on ever shorter timescales. Thus, even though more objects are flung inwards, they are removed so rapidly as to pose significantly less of a threat. The shorter their residence in the inner solar system, the fewer opportunities they have to hit the Earth, and the lower the risk they pose.

Future work

The results from the Centaur population are surprising. We now wonder what we will find for populations derived from the Oort cloud comets and the asteroids. We have started to examine the behaviour of objects in the asteroid belt, as a function of jovian mass. In much the same way as for the first set of simulations, we're looking at what happens when just the mass of Jupiter is varied. In order to do this, we have had to make some assumptions about the nature of the asteroid belt, and how it would look were Jupiter changed in some way. Since it is not possible to take the current asteroid belt as a basis for all the set-ups (the current belt has been heavily sculpted by Jupiter since the birth of the solar system), we have instead created primordial asteroid belts, with outer edges at a location determined by the size of the test Jupiter's gravitational reach. Our results will therefore not only inform us about the jovian effect on the asteroid-related impact rate, but will also produce new results on the manner in which Jupiter sculpted the early evolution of the belt.

Further on, we are going to examine the effect of Jupiter on the Oort cloud comets, essentially building upon the work of Wetherill (1994) through the use of modern computing facilities that allow us to study the situation in far greater detail than was possible in the early 1990s. We then plan to examine the effect that the location and migration of a giant planet has on the impact rate. Beyond this, we intend to expand our work into the study of extrasolar planetary systems, as we attempt to ascertain the effect of jovian planets on the potential for habitability beyond our own solar system.

Summary

Over the years, the idea that the planet Jupiter has acted to shield our Earth from potentially catastrophic impacts has permeated the public and scientific mind. With the recent discoveries of planetary systems around other stars, the question of the shielding offered by such planets to potentially habitable worlds has been thrown into new light – is a Jupiter required in order that a planet have a quiescent enough impact regime that the evolution of life is facilitated? With our work, we are carrying out the first detailed examination of the degree of shielding provided by Jupiter, and have already obtained some surprising results.

For our first population of test objects, cometary bodies evolving inwards from the Edgeworth–Kuiper belt, we have found that our Jupiter provides an impact regime little different from that with no Jupiter present in our solar system. Furthermore, it seems that were Jupiter significantly smaller, the impact rate experienced by the Earth would be considerably enhanced over that which we currently experience. So we now have a situation where the presence of a giant planet in the outer reaches of a planetary system can actually pose a threat to the habitability of terrestrial worlds closer to the system's parent star.

In future work, we will be examining the effect of potential impactors derived from the asteroid belt and from the Oort cloud. We will also vary the orbit of Jupiter and repeat the impact studies, before moving outwards to study extrasolar planetary systems. The goal is to obtain a more detailed understanding of the effect of giant planets on system habitabilities. ●

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