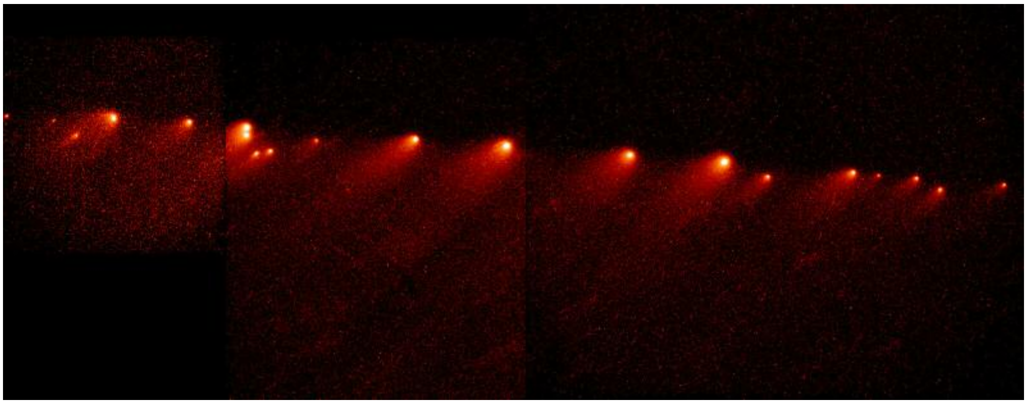
Jupiter: friend or foe?

The planet Jupiter has long been held to be a protective influence toward the Earth, shielding it from asteroids and comets that would otherwise threaten the existence of life on our planet. In recent years, two British scientists have taken a closer look at the role Jupiter plays in determining the rate at which objects collide with the Earth, and have discovered that the situation is far more complicated than was previously thought. So, is Jupiter a friend, or a foe? To find out, read on...

It has long been believed that the planet Jupiter plays a protective role in our Solar System, acting as a celestial law officer to remove potentially hazardous objects before they have the chance to impact upon the Earth. The idea itself is remarkably pervasive, and can be found in everything from teaching materials for young children to academic papers considering the various factors that would determine whether an Earth-like planet around a distant star could host life. It is somewhat startling, therefore, to realise that, until recently, almost no research had been carried out to examine whether the theory was a good fit to reality.

In late 2006, the authors, Dr. Jonti Horner and Prof. Barrie Jones, began a study intended to remedy that lack of research, with the goal of once and for all answering the question "Jupiter – Friend or Foe?".

Within our Solar System lie a great variety of objects. The eight planets move around the Sun on approximately circular paths, and have all but cleared their surroundings of any debris that was once present. Between the orbits of Mars and Jupiter reside a vast population of objects known, collectively, as the Asteroid belt. Despite the fact that the asteroids within the Asteroid belt have been gradually grinding one-another to pieces since the birth of the Solar System, with collisions between asteroids sending debris spinning through space, there is still a significant amount of material moving within the belt – it is estimated that the belt likely contains over a million asteroids

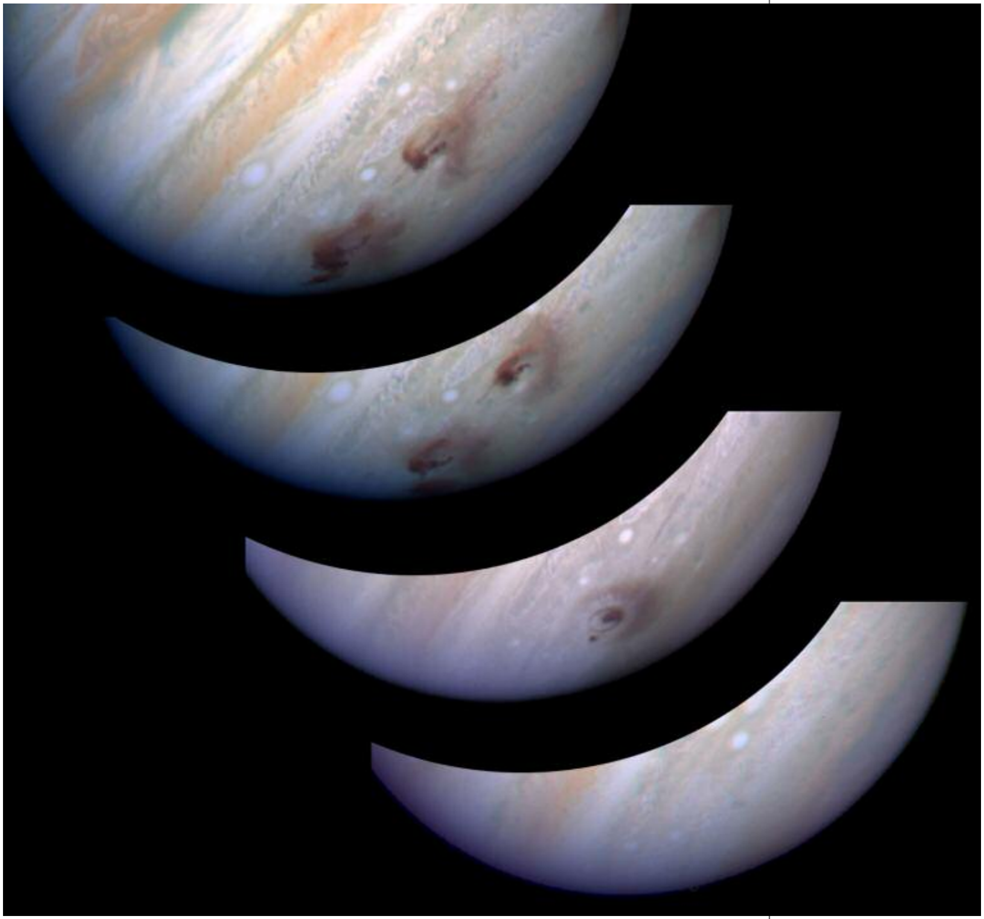


In the spring of 1993, a very curious comet was discovered. This comet was not single, but a string of cometary pieces strung out in a line. Running the orbits backwards showed that these pieces most likely came from a parent body which fell apart in 1992 when it passed very close to Jupiter. [NASA/HST, H. Weaver, T. Smith] greater than one kilometre in diameter. The asteroids in the Asteroid belt move on orbits that, typically, are stable for periods of time comparable to the age of the Solar System, but gravitational stirring, mainly by Jupiter, causes collisions.

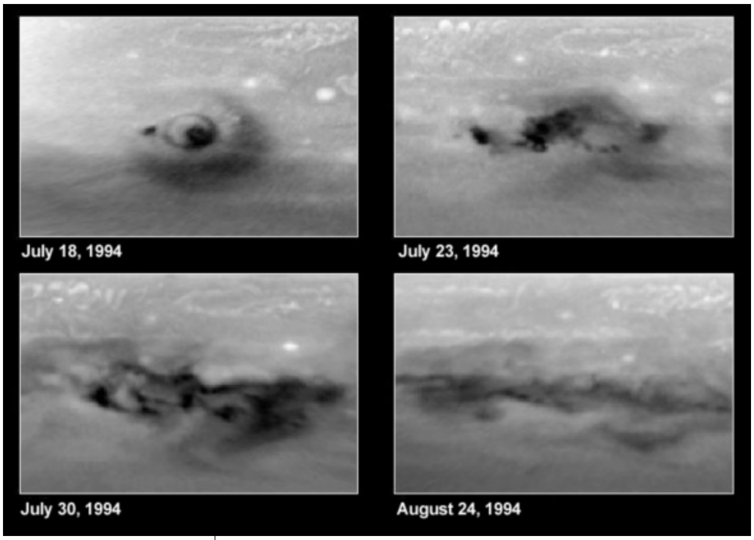
The fragments of the shattered asteroids can be thrown onto new, less stable orbits. Once there, they can gradually work their way into the inner Solar System, where they become near-Earth asteroids.

Once an asteroid is placed on an orbit within the inner Solar System, it will very quickly be removed, either by colliding with the Sun or one of the planets, or having a sufficiently close encounter with one of the more massive planets that it is slingshot out of the Solar System, never to return. In this way, we have a stable reservoir of objects, the Asteroid belt, and an unstable daughter population of potentially threatening objects, the near-Earth asteroids. There are currently over a thousand "Potentially Hazardous Asteroids" known, and it is likely that roughly the same number remain to be discovered. It is well accepted that such objects pose a significant risk to the Earth.

Further from the Sun, just beyond the orbit of Neptune, lies another disk of debris left behind after our Solar System was formed. The Edgeworth-Kuiper belt, as it is known, is similar to the Asteroid belt in many ways – it comprises a vast number of objects (in fact, it is thought that there is much more material in the Edgeworth-Kuiper belt than the Asteroid belt) moving on very stable orbits, such that, were it possible to return to our Solar System in a billion years, the Edgeworth-Kuiper belt would look essentially the same as it does now. The Edgeworth-Kuiper belt has a companion population, the Scattered Disk, which moves in essentially the same region of space, but on somewhat less stable orbits. Again, the bulk of objects within the Scattered Disk will likely still be there in a billion years time, but occasionally, perhaps as a result of a collision between two objects, or the



This mosaic of HST images shows the evolution of one of the impact sites of a fragment of comet SL9. [R. Evans, J. Trauger, H. Hammel and the HST Comet Science Team and NASA/ESA]



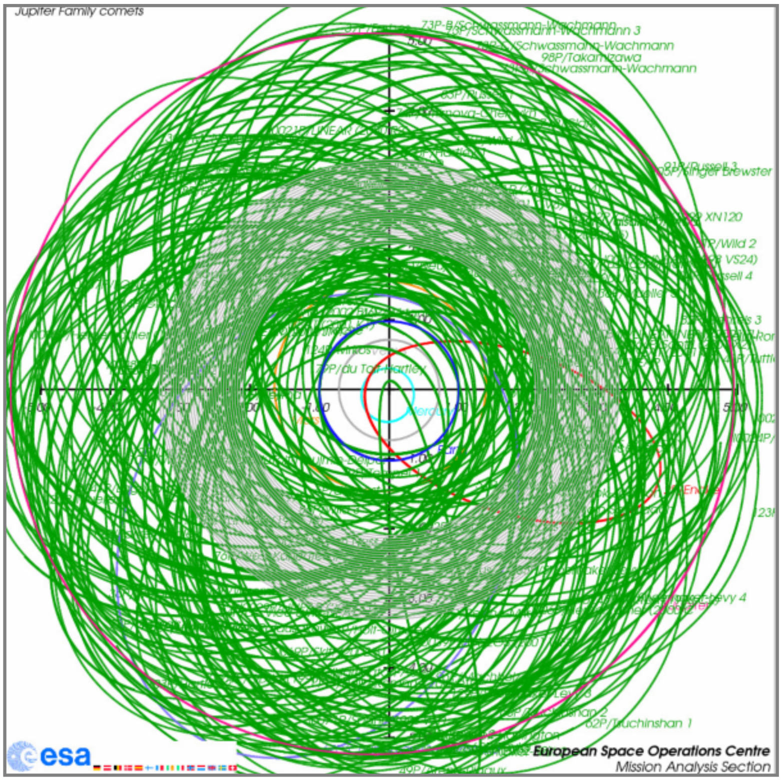
Evolution of the D and G comet impact sites on Jupiter. [NASA, HST Team]

distant perturbations of the giant planets, an object from the Scattered Disk will be injected onto an orbit that brings it closer to the Sun than that of Neptune. From a stable reservoir, this object has now joined a population of icy objects known as the Centaurs, which move chaotically mainly in the region between Neptune and Jupiter, and are scattered backwards and forwards like balls on a pinball table. Eventually, over periods of millions of years, the Centaurs are removed in much the same way as happens for the near-Earth asteroids. Roughly a third of them will be flung into the inner Solar System by Jupiter, to become short period comets. These move on highly eccentric orbits, many of which bring them across the orbit of the Earth. As they swing past the Sun, the icy material which comprises the bulk of them boils off, carrying with it copious amounts of dust, and turning the small dirty snowball into one of the largest objects in the Solar System. The gaseous coma of a comet can be larger than the Sun, and the tail of gas and dust swept outward by the influence of the Solar wind can be longer than the distance from the Sun to the planet Mars! Comets in the Jupiter family move on orbits that typically take just 5 or 6 years to complete, meaning that they swing through the inner Solar System time and time again. The Earth is essentially a moving target in a shooting gallery full of these objects. A very small target, but given enough time, it is certain that it will be hit.

Far, far further from the Sun than the Edgeworth-Kuiper belt and Scattered Disk lies a third vast reservoir of small objects, known as the Oort cloud. Where the Asteroid belt and the various populations just beyond the orbit of Neptune are thought to number millions, or tens of millions of objects greater than one kilometre in diameter, it is thought that the Oort cloud may contain as many as a million, million objects of that minimum size, if not more. In other words, it is thought to contain at least 1,000,000,000,000 dirty snowballs, all greater than 1 kilometre across. Despite this immense population, the density of material in the Oort cloud is remarkably low – in fact, a typical

Example of the fragmentation of a cometary nucleus: 73P/Schwassmann-Wachmann 3 started to break apart in 1995.

object in the Oort cloud likely lies no closer to its nearest neighbour than the distance from the Sun to the planet Uranus (roughly 19 times the distance from the Earth to the Sun). The Oort cloud is thought to stretch out to about halfway to the nearest star – so vast that light would take four years to travel from one side of the cloud to the other. The objects within the Oort cloud typically remain far from the inner Solar System, but gravitational tweaks from passing stars, and the gentle tidal squeezing of the cloud from the mass of our galaxy as a whole, cause a continual stream of these objects to fall into the realm of the planets, where they become visible as the Oort cloud, or long-period, comets.



The orbits of the many Jupiter family comets. The orbit of Jupiter is shown in pink, that of comet Encke in red and that of the Earth in blue. [ESOC/ESA]

So, within our Solar System, we have three distinct stable reservoirs that, between them, contain vast numbers of comets and asteroids left over from the formation of the Solar System (in fact, there are two other reservoirs, both of which may contribute to the Centaur population – the Jovian and Neptunian Trojans, but they're a subject for another day!). There are also three distinct populations of potentially hazardous objects. The near-Earth asteroids, the daughters of the Asteroid belt population, are thought to currently contribute about three-quarters of the impact flux at the Earth, with the remaining quarter being made up by the Jupiter family and Oort cloud comets. Each of these three populations is influenced in dramatically different ways by the gravitational influence of the planets, but for each population, Jupiter plays a pivotal role in determining the fate of that populations members.

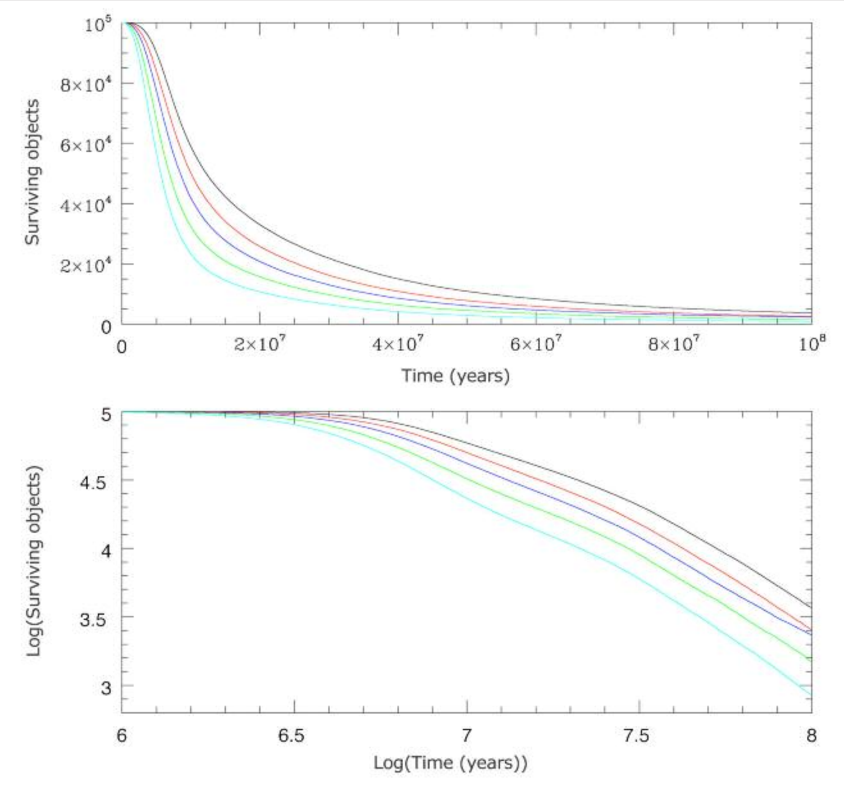
In order to examine the true influence of Jupiter on the impact rate at Earth, it is therefore necessary to consider its effect on each of the three populations of hazard objects discussed above.

The idea that Jupiter acts as a friend to the Earth, shielding us from impacts, like-ly dates back to the 1960s, when it was first becoming widely accepted that the craters on the Earth and the Moon were the result of impacts by objects from space. At that time, very few Jupiter-family comets and near-Earth aster-

The two bright comets of 2007. Above: the short period comet, 17P/Holmes, imaged in early December, and below: the long period comet C/2006 P1 McNaught, photographed on 28th January. [Bob Nanz (San Diego Astronomy Association) - Miloslav Druckmuller (Brno University of Technology)]

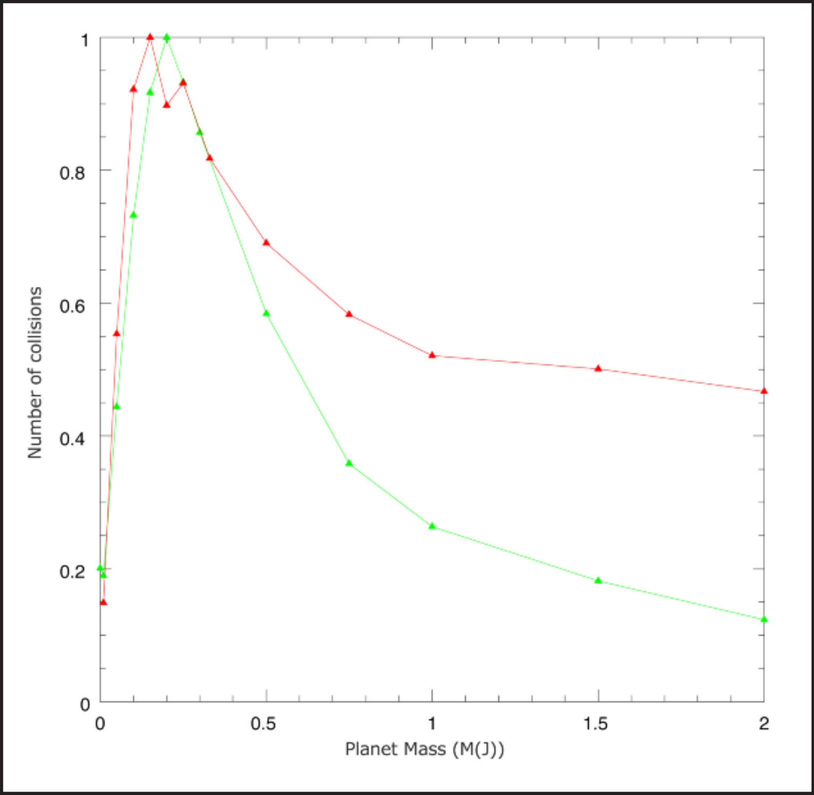
oids were known, and so it was thought that the Oort cloud comets were the main contributors to the impact flux at Earth. A respectable number of Oort cloud comets had been well enough observed at that point that their orbits could be calculated with some degree of accuracy, and a common feature seemed to be that a significant fraction were ejected from the Solar System after passing through it, primarily as a result of distant gravitational perturbations from the planet Jupiter. It was log-ical to assume, therefore, that if Jupiter were not around to eject these objects, they would return again and again, and therefore pose a significantly greater threat to the Earth. Jupiter, it seemed, was a friend.

In the decades since the idea become prevalent, our understanding of our Solar System has changed dramatically. As telescopes and detectors have become more powerful, large numbers of near-Earth asteroids and Jupiter-family comets have been discovered. Indeed, it is now thought that the Oort cloud comets are actually the least threatening of the three populations of potentially hazardous objects, contributing the least frequent impacts. Despite the fact that the idea was based on the way in which Jupiter regularly disposes of Oort cloud comets, the concept of “Jupiter – the friend” has remained widely taught, but poorly studied. In order to remedy this, the authors carried out a series of highly detailed computer simulations, modelling the evolution of large populations of potential impactors under the gravitational influence of the planets for periods of tens of millions of years. Since the three populations of threatening objects behave in distinctly different ways, they looked at each in turn, and simply counted the frequency with which the ob-



The plot above shows the number of long-period comets surviving as a function of time for an initial population of 100,000 objects placed on orbits that bring them closer to the Sun than the orbit of Saturn. Because of the immense orbital periods of these comets, and the tiny probability of any one actually hitting the Earth, we had to use the number remaining in the system as a proxy for the impact threat to the Earth - if a comet is removed, then it never returns to threaten the Earth. So if you have the same inward flux of new comets from the Oort cloud, but fewer are ejected as a function of time, that means you have a greater number returning to imperil the Earth, and a greater impact threat. The upper panel of that plot shows the decay of the number of comets as a function of time - the black line is the scenario with the least massive Jupiter, and the cyan line is the case with the most massive Jupiter. As can be seen, as the mass of Jupiter increases, these long period comets are ever more efficiently ejected from the Solar system, leading to a reduction in the returning population, and therefore a reduction in the impact threat at Earth.

The plot below shows curves for the impact rate at Earth due to objects from the Asteroid belt and the Centaur population (as described in the article) as a function of time. This is a bit more straightforward to understand, since it just shows the number of impacts at our inflated Earth over the course of the integrations. Both for the Asteroids and Centaurs, the peak impact flux is when "Jupiter" is of around the same mass as Saturn in our Solar system, with the rate falling off as Jupiter becomes more or less massive than that value.



jects hit the Earth. To determine the role of Jupiter, they repeated the simulations time and time again, each time using a "Jupiter" with a different mass – from a tiny planet 1/100th the mass of the Jupiter in our own Solar System to a behemoth twice our Jupiter's mass. They even considered scenarios in which no Jupiter was present at all.

Now, if Jupiter truly is a friend to the Earth, then the more massive the planet is (and hence the greater the effect it can have), the fewer impacts the Earth should suffer. On the other hand, if Jupiter is actually a foe, then the frequency of impacts upon the Earth should increase as the planet becomes ever more massive. With this in mind, the authors counted the number of hits on their virtual Earth for populations of objects designed to reproduce the near-Earth asteroids and the Jupiter-family comets. Despite the fact they were able to follow the evolution of hundreds of thousands of such objects for ten million years, the Earth is actually such a small target that, even in the worst case scenarios, very few impacts could be expected. To get around this problem, and in order to obtain meaningful statistics, authors' virtual Earth was far larger than our own planet – essentially enlarging the bulls-eye that the hazardous objects had to aim at. In comparing the outcomes at different "Jupiter" masses it did not matter that all impact rates were increased by the same factor. So, is Jupiter truly a friend, or is it a foe? Lets look at the results they obtained for each population of threatening objects in turn.

This chain of craters on Jupiter's moon Ganymede provides evidence that comets must quite frequently be fragmented by the planet's gravity before colliding with it or its moons.

The near-Earth asteroids

When the authors looked at the way in which the impact rate of the near-Earth asteroids on Earth varied as a function of Jupiter's mass, they found something startling.

Rather than the impact rate falling as the mass of "Jupiter" was increased, something more complicated happened. At low "Jupiter" masses, the impact rate on Earth was very low – "Jupiter" was simply too small to throw objects our way. At high "Jupiter-masses", the impact rate was again relatively low, but at intermediate masses (around a fifth of the mass of the actual Jupiter), the impact rate was far, far higher than at either extreme mass. The impact frequency rose rapidly as Jupiter's mass increased, until this peak value was reached, and then fell away again as Jupiter's mass rose further. Remembering that the near-Earth asteroids, in our own Solar System, are thought to contribute around 75% of the impact threat to the Earth, it is clear from these results that the idea of Jupiter – Friend is, at the very least, a vast over-simplification of the real situation. Why does the impact rate behave this way? Well, it turns out that one of the most efficient ways in which objects are driven out of the asteroid belt to the inner Solar system is through the effects of something called the u6 secular resonance. When Jupiter is of very low mass, the effects of this resonance are very weak, and it therefore is unable to inject much material to the inner Solar system.

As the mass of Jupiter increases, the location of this secular resonance feature gradually moves inwards, through the asteroid belt. The breadth of the resonance increases, and its strength grows, such that, when Jupiter's mass is approximately a fifth of that of "our" Jupiter, the resonant feature carves a vast, broad hole in the distribution of asteroids, able to inject large quantities of material to the inner Solar System.

Comet Encke imaged by Spitzer Space Telescope. Encke is the comet with the shortest known period, 3.3 years, and the one observed at most apparitions. [NASA/JPL-Caltech/M. Kelley (Univ. of Minnesota)]

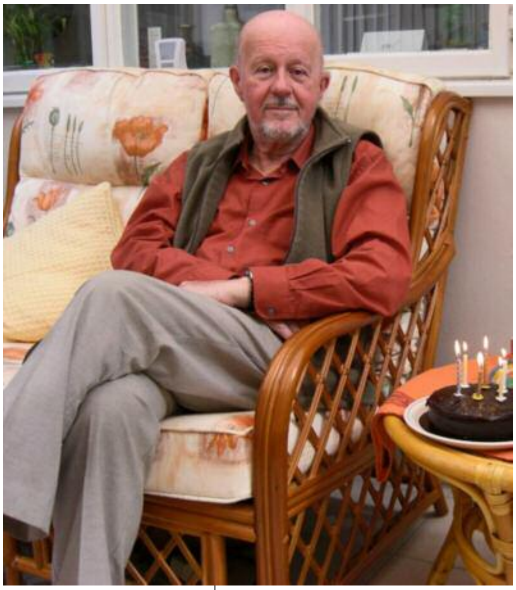
As the mass of the planet grows still further, the strength of the resonant effects also increase, but the location of the resonance moves to the very inner edge of the Asteroid belt, away from the bulk of the material therein. In addition, the resonance gets narrower. Both these effects mean that the efficiency with which the resonance can throw material our way falls off again, leading directly to the reduce impact rates observed.

The Jupiter-family comets

Once again, the work of the authors threw up unexpected results. Much as was the case for the near-Earth asteroids, they found that the impact rate from these objects was very low when "Jupiter" was of low mass. At large "Jupiter masses", the impact rate was still relatively low, but was significantly greater than for the smallest masses. However, when "Jupiter" was around a fifth of its current mass, there was again a broad peak in the impact rate at the Earth. Once again, the planet was not simply a friend, and not simply a foe, but rather could take either role depending on its precise mass.

The reason-ing in this case is somewhat simpler than for the near-Earth asteroids. When "Jupiter" is of very low mass, it is simply too light to easily perturb objects from the outer Solar System (the Centaurs) onto Earth-crossing orbits.

As the mass of the planet increases, it



Professor Barrie Jones, co-author of this article.

gradually becomes more and more proficient in this role, and the number of potentially hazardous Jupiter-family comets increases.

Eventually, as Jupiter's mass continues to grow, it becomes massive enough to eject objects from our Solar System in a single gravitational encounter. From that point on, as the mass increases, it becomes ever more efficient at removing objects from the inner Solar System in this manner, and so, although it injects fresh comets at an ever increasing rate, those comets spend such a short period of time in the inner Solar System before being ejected that the chance of any one of them hitting the Earth falls away, and therefore the total impact flux also decreases.

The Oort Cloud comets

Here, the situation is far simpler. As was known from observations of the Oort Cloud comets, and previous studies of their orbital evolution, Jupiter is particularly efficient at removing these objects from the Solar System, ejecting them, never to return.

As the mass of the planet increases, the efficiency with which Oort cloud comets are ejected also goes up, and therefore fewer of them return to potentially threaten the Earth. As far as the Oort Cloud comets go, then, it does seem that Jupiter truly is our friend. However, since they make up only a relatively small fraction of the impact threat to the Earth, this does little to change the overall conclusion.

Jupiter – Friend and Foe?

The ultimate result of the authors' work is that the role played by Jupiter in determining the frequency with which the Earth suffers collisions with small objects is far more complicated than had previously been thought. Taking the results of their three studies as a whole, it turns out that our Jupiter probably causes the Earth to experience slightly more impacts than we would were the planet not there at all. However, were Jupiter more massive, the impact rate would be lower than we observe. What we can say for definite is that, if Jupiter were actually similar in mass to the planet Saturn, the Earth would experience far more impacts than it does in our own Solar system, and the history of our planet, and the evolution of life upon it, would have taken a very different, and far more chaotic course.

Jonti Horner is a Research Fellow at the University of New South Wales, having recently moved to Australia from the UK. He is involved with the search for planets around other stars, lead by Prof. Chris Tinney at UNSW, but continues to carry out detailed computation studies of the formation and evolution of our own Solar system, as well as research into the nature of planetary habitability. He is a committee member of the Astrobiology Society and the Astrobiology Society of Great Britain, and has a personal website at http://jontihorner.com.

Barrie Jones is Emeritus Professor of Astronomy at the Open University. Shortly after the first exoplanet discovery was announced in 1995 he set up research into whether the "Goldilocks zone" of each exoplanetary system offered stable orbits for the as yet undiscovered Earth-like planets. This work was carried out with two PhD students. More recently he has been working with Dr Horner on whether Jupiter shields us from excessive impacts by asteroids and comets. As well as contributing to the physics and astronomy courses of the Open University, he has, before and after "retirement", written his own astronomy books. The latest of these is "Pluto: Sentinel of the Outer Solar System", published by Cambridge University Press in August 2010. His personal website is at http://barriewjones.com.