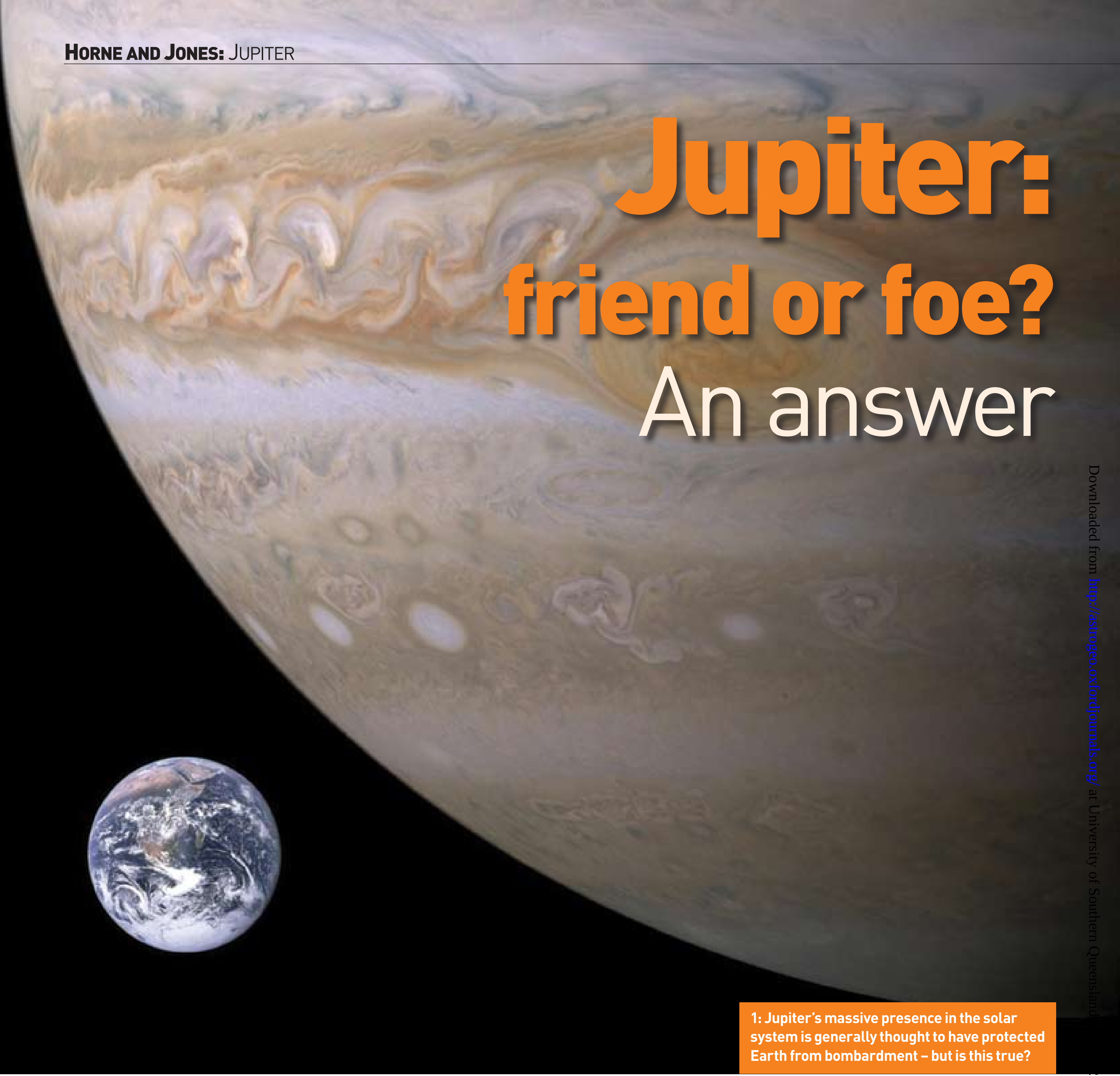
Jupiter: friend or foe?

An answer



1: Jupiter's massive presence in the solar system is generally thought to have protected Earth from bombardment – but is this true?

Barrie Jones and Jonti Horner summarize the results of models addressing the role of Jupiter in protecting – or otherwise – the Earth.

It has long been assumed that the planet Jupiter acts as a giant shield, significantly lowering the impact rate of minor bodies on the Earth. However, until recently, very little work had been carried out examining the role played by Jupiter in determining the frequency of such collisions. In a series of papers published in the *International Journal of Astrobiology* (Horner and Jones 2008a, 2009, Horner *et al.* 2010), we examined the degree to which the impact rate of asteroids, short-period and long-period comets on Earth is enhanced or lessened by the presence of a giant planet on a Jupiter-like orbit. This constitutes an attempt to more fully understand the impact regime under which life on Earth has developed. In an earlier article in *A&G* (Horner and Jones 2008b) we presented the preliminary results of our study of the threat posed by short-period comets. Here, we bring together a summary of all three papers and answer the question: "Is Jupiter a friend or a foe?"

The Earth has been bombarded by asteroidal and cometary bodies through its history. As well as causing local mayhem in the biosphere, larger impacts can cause mass extinctions, and will therefore have had a major influence on the survival and evolution of life (Alvarez *et al.* 1980, Sleep *et al.* 1989). However, the effects of such impacts are not solely damaging to the development of advanced life. Indeed, without extinctions, far fewer empty ecological niches would appear to promote the emergence of new species. Nevertheless, one can imagine scenarios in which really large impacts could occur so often that the evolution of a biosphere would be stunted by overly frequent mass extinctions, each bordering on (or resulting in) global sterilization. Without Jupiter present, it has been argued, such frequent mass extinctions would have occurred on the Earth (Ward and Brownlee 2000).

It is widely accepted in the scientific community (and beyond) that Jupiter has significantly reduced the impact rate of minor bodies on the Earth. It is perhaps surprising, when one considers how widely this well established view of Jupiter's protective role is held, that very little work has been carried out to back up that hypothesis. Indeed, until recently, almost no studies have examined the effects of the giant planets on the flux of minor bodies through the inner solar system. In the sole study carried out before the 21st century, Wetherill (1994) suggested that, in systems containing giant planets which grew only to the mass of around Uranus and Neptune, the impact flux of cometary bodies experienced by any terrestrial planet could be a factor of a thousand times greater than that seen today.

In our solar system, there are two distinct populations of cometary bodies. The first, the long-period comets, move on orbits that take thousands, or even a few million, years to complete. These objects are sourced from a vast reservoir known as the Oort cloud, a predominantly spherical distribution of 10^{12}–10^{13} icy bodies, the great majority of which are smaller than 10 km in diameter, and occupy a thick spherical shell approximately 10^3–10^5 AU from the Sun (e.g. Horner and Evans 2002). Objects can be perturbed inwards from this cloud by various mechanisms (including gravitational tweaks from passing stars, and the effects of the galactic tide). Many acquire orbits that penetrate the inner reaches of the solar system, thus becoming the long-period comets (periods of more than about 200 years, with the full range of orbital inclinations). The other population of cometary bodies are the short-period comets. Again, the great majority of these objects have nuclei less than 10 km in diameter, but rather than moving on orbits that take thousands of years to complete, the majority move on orbits with periods comparable to, or shorter than, the average human lifetime. The short-period comets, then, are comets that return time and time again, and are well documented and studied. They can in turn be broken in to two main sub-populations. The Halley types are a small population of comets moving on relatively long-period orbits (for short-period comets!).

The great majority of short-period comets, however, are members of the Jupiter family. These comets move on orbits that typically take just a few years to complete, and have their aphelia (greatest distance from the Sun) in the vicinity of Jupiter's orbit. While the source of the Halley-type comets is still poorly understood, the proximate source of the Jupiter family are objects known as the Centaurs, which move between the orbits of Jupiter and Neptune (e.g. Horner *et al.* 2003, 2004a, 2004b). The source of the Centaurs themselves, however, is still under some debate. It seems likely that they originate within the menagerie of objects that orbit around, or beyond, the orbit of Neptune. The first source population suggested for these objects is the Edgeworth–Kuiper belt, a population of icy-rocky bodies, predominantly less than a few tens of km across, orbiting beyond Neptune in fairly low-inclination orbits. The objects currently known in the Edgeworth–Kuiper belt range in size to over 2000 km in diameter, but large objects are over-represented because they are easier to discover. A whimsical analogy is with wildlife on the plains of Africa – even though there are billions of flies within a few kilometres, it's far easier to see the few elephants also present. However, it seems likely that the objects moving within that belt are too dynamically stable to be the predominant source of Centaurs.

Fortunately, associated with the Edgeworth–Kuiper belt is a more dynamically excited component, known as the scattered disc (see e.g. Lykawka and Mukai 2007, Gomes *et al.* 2008). The orbits of objects within the scattered disc are typically somewhat unstable, and it is thought that a steady trickle of objects evolve inwards from this belt to become the Centaurs. In addition, it has recently been proposed (e.g. Horner and Lykawka 2010a, 2010b) that the newly discovered Neptune Trojan family could contribute a significant fraction of the material moving into the Centaur region. Once objects have become Centaurs, their orbits evolve on relatively short timescales, under the perturbative influence of the giant outer planets. They are scattered chaotically, with a typical eventual fate of ejection from the solar system. Before their removal from the system, however, up to a third of Centaurs can be expected to become short-period comets, replacing those lost to fragmentation, impacts, devolatilization and ejection from the solar system to maintain a roughly steady-state cometary population.

In his 1994 paper, Wetherill used Monte-Carlo simulations of a population of bodies that initially occupied eccentric, low inclinations orbits with semi-major axes between 5 and 75 AU. Because Jupiter orbits at 5.2 AU, such a population is bound to be far more sensitive to the mass of Jupiter and Saturn than bodies derived from the trans-Neptunian region, which would greatly exaggerate the shielding provided (by a factor of 1000). In addition, Monte-Carlo simulations, while necessary given the slow computers of the day, yield numerical data that are significantly less reliable than modern orbital integrators. Despite this, Wetherill's results were very convincing and for a decade no more work was done to examine this subject. In more recent times (see our 2008a paper), a study by Laasko *et al.* (2006) led to the conclusion that Jupiter "in its current orbit, may provide a minimal amount of protection to the Earth". They also mention the work of Gomes *et al.* (2005), from which it is clear that removing Jupiter from our solar system would result in far fewer impacts on the Earth by lessening or removing entirely the effects of the proposed Late Heavy Bombardment of the inner solar system, some 700 Myr after its formation. However, in that work, nothing is said about more recent times.

The idea that Jupiter has protected the Earth from excessive bombardment dates back to when the main impact risk to the Earth was thought to arise from the Oort cloud comets. The idea probably originated in the 1960s, when craters were first widely accepted as evidence of ongoing impacts upon the Earth and far more long-period comets were known than the combined numbers of short-period comets and near-Earth asteroids. It is well known that a large fraction of such objects are expelled from the solar system after their first pass through the planetary region, mainly as a result of Jovian perturbations. Hence, by significantly reducing the population of returning objects, Jupiter lowers the chance of one of these cosmic bullets striking the Earth. However, in recent years, it has become accepted that near-Earth objects (many of which come from the asteroid belt, others from the short-period comet population) pose a far greater threat to the Earth than that posed by the Oort cloud comets. Indeed, it has been suggested that the *total* cometary contribution to the impact hazard may be no higher than about a quarter (e.g. Chapman and Morrison 1994, Morbidelli *et al.* 2002).

The effect of Jupiter on each of the three immediate source populations of potentially hazardous objects – the asteroid belt, the Centaurs, and the Oort cloud – has been neglected, and in order to ascertain the overall effect of Jupiter on the terrestrial impact flux it is important to understand its influence on each of the three kinds of bombarders.

We examined the effect of changing the mass of a giant planet in Jupiter's orbit on the impact rate on Earth by each of the three populations of bombarders described above. There follows an account of this work and its outcome.

Varying the mass of a giant in Jupiter's orbit – bombardment from the asteroid belt

In our 2008a paper we examined the effect of changing "Jupiter's" mass on the impact rate experienced by the Earth from objects flung inwards from the asteroid belt. We faced some problems in simulating the impact flux.

Of the three parent populations that supply Earth's impacting bodies, the asteroids are believed to pose the greatest threat. However, in creating a swarm of test asteroids that might evolve on to Earth-impacting orbits, we face huge uncertainties, particularly relating to the distribution of the asteroids at the start of the integrations.

Jupiter has been perturbing the orbits of the objects currently observed in the asteroid belt since its formation. This means that using the current belt as the source in runs with different "Jupiters" would be misguided. It is therefore important to attempt to construct a far less perturbed initial population for the asteroid belt, if one wishes to observe the effect of changing Jupiter's mass on the impact rate. Our 2008a paper details how we settled on a population distribution, $N(a)$ at $t = 0$, given by

$$N_0(a) = k(a - a_{\min})^{1/2} \tag{1}$$

where $N(a)$ is the number of asteroids at a distance a from the Sun, k is a constant and $a_{\min}$ is the inner boundary of the asteroid distribution.

The value of $a_{\min}$ was chosen to be 1.558 AU, equal to the orbital semi-major axis of the planet Mars, 1.52 AU, plus three Hill radii. The Hill radius R_H of a planet is given by

$$R_H = a_p \left(\frac{M_{\text{planet}}}{3\, M_{\text{Sun}}} \right)^{1/3} \tag{2}$$

where a_p is the semi-major axis of the planet's orbit, and M denotes mass. The Hill radius is the distance from the planet at which its gravitational attraction on a small third body is of the same order as the gravitational interaction of each body with the star they orbit (within the restricted three-body problem). Three Hill radii from a planet is therefore a reasonable approximation to the "gravitational reach" within which the small body is likely to experience strong perturbations by the planet that could lead to it being ejected from its orbit. Strictly, equation 2 represents a simplified case in which the eccentricity of the planet's orbit is assumed to be zero. As the eccentricity of a planet's orbit increases, so does the outward "reach" over which it can strongly influence nearby small bodies. Because the orbital eccentricity of Mars is 0.093, a more cautious value for the multiplier for its outward reach should be about 5 (Jones *et al.* 2006). However, since there are no asteroids at $a_{\min}$ (equation 1), adopting such a cautious value over the standard three Hill radii actually makes little difference. Mars has a mass 0.107 times that of the Earth. However, in our simulations, we adopted a value of 0.4 Earth masses. This is a crude attempt to allow for the likely greater mass of Mars when "Jupiter" has a smaller mass. This increases slightly the perturbation of the small number of inner asteroids, which has an insignificant effect on our results.

The outer boundary, $a_{\max}$, was placed three Hill radii within the orbit of the giant planet (interior to the 5.203 AU of "Jupiter's" orbit). Closer to the planets than this, asteroidal bodies are unlikely to form, as the ongoing perturbation of the orbits of debris in those regions would result in the mean collision velocity between two objects being higher, resulting in typically destructive rather than constructive collisions. For a Jupiter mass giant, $a_{\max}$ is at 4.14 AU, and 4.71 AU at 0.1 Jupiter masses. Because the outer boundary is interior to "Jupiter's" orbit, and given "Jupiter's" orbital eccentricity of only 0.049, a multiplier of three is appropriate (Jones *et al.* 2006).

It is important to note that our main conclusions below concerning the variations of the impact rate on Earth as a function of giant planet mass are not sensitive to the precise form of $N_0(a)$.

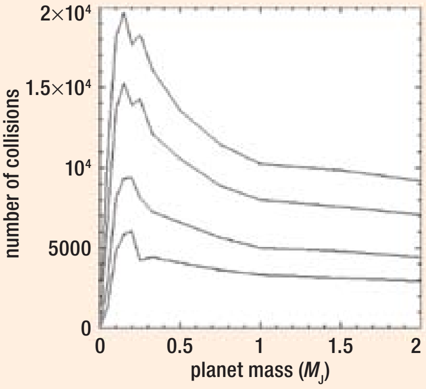
A total of 10^5 test particles were created using the cumulative probability derived from equation 1, enough for us to obtain reasonable collision statistics. The remaining orbital elements were randomly distributed, with orbital inclinations of 0–10° and eccentricities of 0.0–0.1. This range encompasses the majority of asteroids known today – and prior to their 4.5 Gyr of evolution would doubtless have covered even more of the initial population. The objects created in this way represent a disc of debris that has received a moderate, but not excessive, amount of stirring during the formation of the planets (e.g. Ward 2002).

The test particles were then followed for a period of 10 million years using the Hybrid integrator contained within the *MERCURY* package (Chambers 1999), under the influence of the planets Earth, Mars, Jupiter, Saturn, Uranus and Neptune (Mercury and Venus could safely be excluded). Simple test integrations were carried out to examine the effect of the cross-sectional area of the Earth on the impact flux experienced. As expected, the impact rate was found to be proportional to the cross-sectional area of the Earth, with gravitational focusing having a negligible effect. In order to enhance the impact rate to obtain reasonable impact statistics, we therefore inflated the Earth to a radius of 10^6 km. Within our integrations, the asteroids interacted gravitationally with the planets and the Sun, but not with each other; in this sense they were mass-less. This is a good model – a typical asteroid is at least 10^{11} times less massive than Jupiter!

At the start of our integrations, Jupiter is fully formed, and already moving on its current orbit (in other words, we consider that any migration the planet experienced during its formation and evolution has ceased at our $t = 0$). The integration duration was chosen to provide a balance between the required computation time and the statistical significance of the results obtained.

The "Jupiter" used in our runs was modified so that we ran 12 separate masses. In multiples of Jupiter's mass, M_J, these are: 0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.33, 0.50, 0.75, 1.00, 1.50 and 2.00. The orbital elements for each "Jupiter" were identical to those of Jupiter today. Similarly, the elements taken for the other planets in the simulations were identical to those today: the only difference in the planetary setup between one run and the next was the change in Jovian mass – all other variables were constant.

It is obvious that, in reality, were Jupiter a different mass, the architecture of the outer solar system would probably be somewhat different. However, rather than try to quantify the uncertain effects of a change to the formation of our own solar system, we felt it best to change solely the mass of the "Jupiter", and work with a known, albeit modified, system, rather than an uncertain theoretical construct. In the case of the flux of objects moving inwards from the asteroid belt, this does not seem a particularly troublesome assumption, since Jupiter is by far the dominant influence.

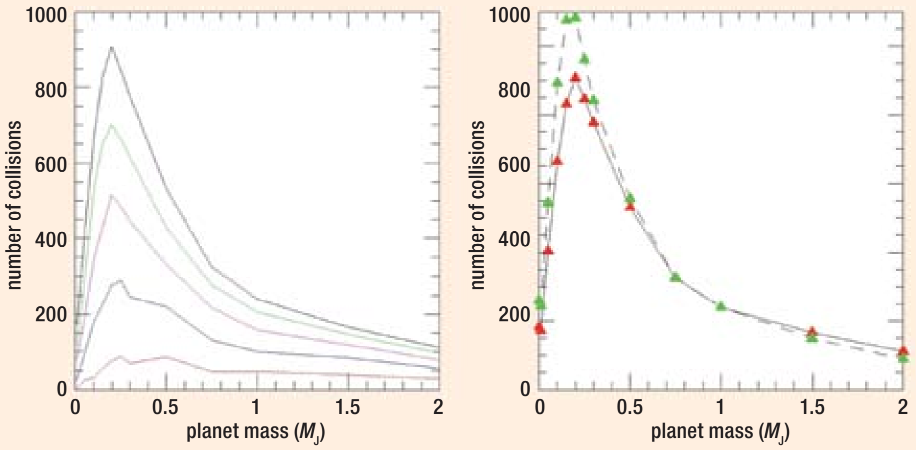


2: The number of asteroid collisions with the inflated Earth as a function of "Jupiter's" mass, at (bottom to top) 1, 2, 5 and 10 Myr into the integration.

The complete suite of integrations, each spanning a simulated time of 10 Myr, ran for some six months of real time, spread over the cluster of computers sited at the Open University. This six months of real time equates to more than 20 years of computation time, and resulted in measures of the impact flux for each of the 12 "Jupiters". The eventual fate of each asteroidal body was also noted.

When considering our results, in the simplest terms, there are two roles that Jupiter can play in the modification of the Earth's impact flux. If Jupiter is solely a "friend", shielding Earth from impacts, then we would expect that the higher Jupiter's mass, then the lower the impact flux at Earth would be. On the other hand, if Jupiter is actually a "foe", then we would expect the impact flux to increase as a function of Jovian mass. It seemed reasonable to expect that our results would reveal that one or the other of these roles would dominate, and therefore we expected that a plot of impact flux versus Jovian mass would demonstrate a fairly straightforward increasing or decreasing tendency. Figure 2 shows the form of the flux–mass relationship from our simulations in which the asteroids were the source population.

These results were surprising. At 1.00 M_J, the number of impacts on the Earth is about 3.5 times the number at 0.01 M_J – hardly a shield! Between these two "Jupiter" masses there is a peak at around 0.2 M_J where the number of impacts is nearly double that at 1.00 M_J. Why? The answer comes down to the effect of



3 (Left): The number of collisions on the (inflated) Earth versus the mass of "Jupiter" at the following times into the integration: bottom to top, 2, 4, 6, 8 and 10 Myr.
(Right): The solid line is a repeat of the 10 Myr curve at left, with red triangles marking the data points; the dashed line with green triangles shows the red data points adjusted upwards to take account of the variation in the half-life of the potential impactors with respect to the half-life at 1 M_J (a longer half-life means a higher steady-state population of Centaurs and, in turn, an enhanced impact rate over that measured in our integrations).

something known as a "secular resonance".

Just as the spin axes of objects within our solar system precess over time (the Earth's, for example, taking some 26 000 years to complete one full precession), the rotational elements of an object's orbit (the argument of perihelion ω and the longitude of the ascending node Ω) also precess. The rate at which these elements precess varies from one object to another, and it is when the period of the precession of one of these elements for one object is an integer ratio of the precession period of an element for another object that a secular resonance occurs. Because the orbits of the two objects are precessing at rates that are an integer ratio of one another, this can allow the two objects to gravitationally perturb one another's orbits over very long timescales, in a manner that would not necessarily be expected on first examination of their orbits. This is particularly interesting when the orbit of a small body (such as an asteroid) is in secular resonance with the orbit of a large planet (such as Jupiter). The long-term perturbations on the orbit of the asteroid from the giant planet can act to significantly alter the asteroid's orbit, and can lead to its eventual destabilization and injection to the inner solar system. Importantly, the rate at which orbits in the solar system precess varies if the masses of the planets are changed – and so the locations in the solar system at which an asteroid will experience secular resonance with, say, Jupiter, move if you change the mass of that planet.

This, then, brings us to our explanation of the unexpected behaviour of the impact flux of asteroids on Earth as a function of Jovian mass that can be seen in figure 2. At Jupiter's current mass, a secular resonance known as the υ_6 resonance is well known to play a significant role in the transport of material from the inner regions of the asteroid belt to the inner solar system. As things stand, the resonance is almost clear of the inner edge of the asteroid belt, and only has a significant effect on objects near that inner edge. As we examined the final form of the asteroid distribution $N(a)$ at the end of our integrations, it quickly became apparent that the lower Jupiter's mass, the further from the Sun the resonance was located, and hence the more objects could be affected and perturbed by it. This was evidenced by the presence of a large "hole" developing in the middle of the belt, as asteroids were perturbed from their orbits, and scattered out of the main belt.

The largest such "hole" appeared for those runs with the greatest impact flux on Earth – around 0.2 Jupiter masses. Below that mass, although the hole continued its outward motion, the mass of Jupiter became so low that the perturbations experienced by the asteroids were sufficiently gentle that fewer were lost from the belt, which in turn led to fewer reaching the Earth, and fewer impacts. Above the current mass of Jupiter, the resonance left the inner edge of the belt almost completely, resulting in ever smaller amounts of material being thrown inward. For plots showing the motion of this "hole", we direct the reader to our 2008a paper.

Bombardment by short-period comets

In our 2009 paper (and our previous article in *A&G*), we examined the effect of Jupiter on the impact flux at Earth resulting from the short-period comets. Since the short-period comets themselves are already under Jupiter's influence, we created a test population based on their parent objects, the Centaurs (e.g. Horner *et al.* 2004a, 2004b, Levison and Duncan 1997).

As for the asteroids, we needed to be careful to avoid selecting an initial population that had already been sculpted by Jupiter's influence. To achieve this, we searched the catalogue of all known Centaur and trans-Neptunian objects listed by the Minor Planet Centre for all objects with perihelia in the range 17–30 AU. The lower limit was set to ensure that the population chosen had not recently been influenced by the giant planet in Jupiter's orbit. As a result, no object was selected that had a perihelion distance closer to the Sun than Uranus. This gave a total of 105 objects, including Pluto. Pluto was removed, to leave 104 objects. The orbits of each of these objects were then "cloned", creating a suite of 1029 test particles, spread out in a regular 7×7×7×3 grid in a–e–i–ω space, centred on the nominal orbit of the object in question. The grid spacings were 0.1 AU in a, 0.05 in e, 0.5° in i, and 5° in ω. As for the asteroids, we then followed the evolution of these bodies in planetary systems containing "Jupiters" of various mass for a period of 10 Myr, using the Hybrid integrator within *MERCURY* (Chambers 1999). Thirteen different scenarios were examined, 12 with Jupiter masses of between 0.01 and 2.00 times the mass of our Jupiter, and a final case where no Jupiter was present. Aside from varying the mass of Jupiter, nothing was changed from one scenario to the next. Once again, an inflated Earth (radius 10^6 km) was included in the integrations, to get the best possible collision statistics, and the planets Jupiter, Saturn, Uranus and Neptune were also included. As is standard for dynamical studies of the outer solar system, Mars, Venus and Mercury were left out of the solar system – their presence would merely have caused the calculations to take significantly longer, while having no real effect on the outcome of the runs. As before, the test particles interacted solely with the planets and the Sun, not with one another.

Figure 3 shows the main outcome. As in figure 2, figure 3 (left) shows that there is again a peak around 0.2 M_J. In this case, however, the difference between the peak flux and that for a system at 1.00 M_J is larger, with the maximum number of collisions being 4.5 times that at 1.00 M_J. Furthermore, it is apparent that the number of collisions at 1.00 M_J is about 40% greater than that at 0.01 M_J. This difference is not as great as was seen for the asteroids, but again it seems that Jupiter is not acting as a shield.

Figure 3 (right) shows the 10 Myr outcome from figure 3 (left) as the solid line with data points marked as red triangles. The dashed line with green triangles shows the red data points adjusted upwards to take account of the variation in the half-life of the potential impactors with respect to the half-life at 1 M_J. This is an important adjustment because the Centaurs, from which we derive our short-period comets, are a transient population that is re-supplied from the trans-Neptunian region (from the various reservoirs mentioned above). The half-life of the test population ranges from 87.3 Myr at zero giant mass to 48.4 Myr at 2.0 M_J. Clearly, if the inward flux from the source reservoir is constant, but the rate at which material is removed changes, then the instantaneous population of Centaurs would also change. Systems with a longer half-life would therefore have a higher instantaneous Centaur population than those with short half-lives. Once this is taken into account, the green data points show that the number of collisions at 1.00 M_J is about the same as that at 0.01 M_J.

While for the asteroids the key reason for the shape for the flux–mass relationship was the influence of the ν_6 secular resonance, the story for the Centaurs is somewhat more straightforward. "Jupiter" plays two roles, in this case. On the one hand, close encounters with the planet can perturb Centaurs onto orbits that pass through the inner solar system from orbits which had them moving further out. On the other hand, Jupiter can equally perturb objects moving on Earth-crossing orbits in such a way that they no longer encounter the planet. Indeed, as the mass of Jupiter increases, it becomes capable of ejecting objects from the solar system in a single encounter. It is the balance of these two contrasting effects that determines the impact flux from short-period comets at the Earth.

At low "Jupiter" masses, the planet only has a small Hill sphere, and so encounters that can strongly perturb the orbit of Centaurs are infrequent. As the mass increases, the planet becomes able to perturb Centaurs strongly enough that they can be placed on Earth-crossing orbits. Strongly perturbing encounters are quite infrequent, however, so Centaurs placed on such orbits can remain Earth-crossing for long periods of time, resulting in an impact rate that climbs with the mass of the planet. Eventually, the planet becomes massive enough that perturbing encounters become more frequent, and the deepest become capable of ejecting the object from the solar system entirely. At this point, the efficiency with which "Jupiter" clears objects from threatening orbits becomes such that the impact flux begins to fall as the mass continues to increase.

Bombardment by comets from the Oort cloud

In our 2010 paper, we presented the results of simulations examining the role of Jupiter in modifying the impact risk on Earth due to the long-period comets, which come from the Oort cloud (e.g. Oort 1950). Long-period comets are traditionally defined to be comets with orbital periods greater than 200 years, although those on their first pass through the inner solar system typically have orbital periods over 10^5 years. These "new" long-period comets are sent into the inner solar system as a result of distant gravitational perturbations from passing stars, passing dense molecular clouds, and by the galactic tide (Emel'yanenko *et al.* 2007, Nurmi *et al.* 2001).

In order to create a swarm of objects that might evolve onto Earth-impacting orbits, we randomly generated a population of 100 000 test particles, with perihelia located in the range 0.1–10 AU and aphelia between 10 000 and 100 000 AU. The population was structured in an attempt to emulate the observed aphelion distribution of long-period comets. The perihelion distance q was determined as follows

$$q = 0.1 + [(q_{max} - q_{min})^{3/2} \times random]^{2/3} \qquad (3)$$

where q_{max} and q_{min} are the maximum and minimum possible perihelion distances of 0.1 and 10 AU, respectively, and *random* is a random number between 0 and 1, generated within the cloning program. This resulted in approximately 3% of the initial sample having orbits that cross the Earth's orbit (Earth-crossing orbits), and approximately 38% being on initially Jupiter-crossing orbits (orbits with q less than, or equal to, 5.203 AU). This distribution is a simple, but effective, attempt to fit the known distribution of new Oort cloud comets (see e.g. Horner and Evans 2002, and references therein). For further details see Horner *et al.* 2010.

The inclination of a comet's orbit was set randomly between 0 and 180°, and the longitude of the ascending node and the argument of perihelion were each set randomly between 0 and 360°. Finally, the location of the comet on its orbit at the start of the integration (the initial mean anomaly) was set randomly between 0 and 360°.

Once the cloning process was complete, the 100 000 test particles had been distributed on a wide variety of long-period orbits. The dynamical evolution of these particles was then followed for a period of 100 Myr, using the Hybrid integrator contained within a version of the *MERCURY* (Chambers 1999) package that had been modified in order to allow orbits to be followed in barycentric, rather than heliocentric, coordinates. The integration length and the number of planets included were chosen to provide a balance between reasonable computation time and the statistical significance of the results obtained.

Whereas in our two earlier papers we counted the number of collisions on an (inflated) Earth, for the Oort cloud comets a different approach was needed. The orbital period of Oort cloud comets is so great that, even in a 100 Myr simulation, very few close encounters with the Earth would be expected even were the Earth to be greatly inflated. Therefore, in order to directly determine the rate of impacts on the Earth, we would have had to simulate a vast number of test particles, many orders of magnitude higher than that used. This, in turn, would have required an unfeasibly large amount of computation time. Therefore, we needed a proxy for the impact rate. Initially, we chose to use the number of comets that survived as the orbital integration proceeded.

4: The long-period comet C/1995 01 Hale-Bopp, which swept through the inner solar system in 1997. (Dr Francisco Diego, University College London)

Over the course of the integrations, comets were followed as they moved around the Sun until they hit Jupiter, Saturn, or the Sun, or were ejected from the solar system entirely. Since comets thrown to sufficiently large distances will clearly never return – because of the unmodelled gravitational effects of nearby stars, the galactic tide and molecular clouds – the particles in our simulations were considered "ejected" when they reached a barycentric distance of 200 000 AU – twice the maximum initial aphelion distance. Note that our work focused on comets after they had been sent inwards, so the fate of departing survivors beyond 200 000 AU was not of importance in our work.

As the comets in our simulations orbited the Sun, they suffered orbital perturbations around the time of perihelion passage that resulted from the distant influences of Jupiter and Saturn. These act to either lengthen or reduce the orbital period of the comet in a random manner. However, the comets are so loosely bound to the Sun that only a moderate change in their orbital angular momentum is sufficient to remove them from the system entirely. Clearly, a comet whose orbital period is reduced will return to potentially threaten the Earth, while one that is ejected from the system can never return to pose a threat. An example of the former type is C/1995 O1 Hale-Bopp (figure 4), a comet that most probably originated in the Oort cloud, but was then captured to the much shorter period orbit upon which it was observed at its last apparition. Following further distant perturbations during that perihelion passage, its orbit was shortened still further, so that it

Table 1: The number of surviving Oort cloud comet clones at various times into the orbital integration

mass (M_J)	0	1 Myr	10 Myr	100 Myr
0.00	100000	99982	58949	3689
0.25	100000	99861	50138	2551
0.50	100000	99681	41835	2337
1.00	100000	99314	32334	1495
2.00	100000	98659	23253	852

M_J is the mass of Jupiter.

will only take approximately 2500 years for it to complete its next orbit around the Sun – in astronomical terms, the blink of an eye! In other words, for a given population, the greater the number of objects that survive, the higher the impact rate experienced by the Earth.

Non-gravitational forces (such as those that would result from jetting or splitting of the cometary nucleus) were neglected, and no perturbations were applied to the comets to simulate the effect of passing stars, the galactic tide, and passing molecular clouds. Although this means that our simulations are a simplification, the effect of these distant perturbations would be the same for all masses of Jupiter, and so they can safely be neglected here.

As in our earlier work, the mass of "Jupiter" used in our simulations was modified from one scenario to the next. In total, five distinct scenarios were considered. Systems with "Jupiters" of mass 0.25, 0.50, 1.00 and 2.00 times the mass of our Jupiter were studied, together with one in which no Jupiter was present. As before, the only difference between scenarios was the mass of Jupiter – all other parameters were constant. Since Jupiter and Saturn have a far greater effect on the evolution/ejection of fresh Oort cloud comets, these were the only massive bodies included in the integrations, other than the Sun. While this represents a further simplification of the planetary system over our previous runs (in which the effects of Uranus, Neptune and the Earth were also included), it is clearly not an unreasonable approximation. As the comets considered in this work were dynamically "new" (i.e. freshly injected from the Oort cloud), the influence of the planets on their initial orbits is negligible. The complete suite of integrations ran for some four months of real time, spread over the cluster of machines sited at the Open University. This span of real time equates to more than 13 years of computation time, and resulted in measures of the comet survival rate in each of the five mass scenarios.

Table 1 shows the number of surviving comets at a sample of times into the 100 Myr integrations, for the five scenarios tested. The differences between the masses quickly become apparent, with the high-mass cases seeing a significantly more rapid loss of comets than those of low-mass Jupiters. This enhanced ejection rate for the higher Jupiter masses is apparent even after just 1 Myr, and continues through to the very end of our simulations, by which point, in all cases, only a small fraction of the initial cometary population remains.

It is interesting to note that, even when no Jupiter is present, there is still a significant depletion in the population of long-period comets by the end of the runs. With no Jupiter present (zero "Jupiter" mass), Saturn (as the only remaining massive body in the integrations) must be solely responsible for ejecting the Oort cloud comets. This is actually not particularly surprising – Saturn is a very massive planet in its own right, and is more than sufficient to cause the ejection of large numbers of long-period comets on these kinds of timescales. It is, however, a welcome reminder that the impact regimes experienced in planetary systems are affected by many different factors, a point we will return to in the discussion.

When considering our results based on the initial proxy of ejection rate, it is important to ensure that that measure is actually a suitable proxy for the impact flux. It seemed possible, for example, that the collision rate on Earth might not simply be proportional to the number of surviving Oort cloud comets. Two additional possibilities, in particular, seemed worthy of further investigation, to ensure that our initial assumption was correct:

- Given the spread of cometary orbits investigated, it was important to examine whether there could be preferential survival of *either* the Oort cloud comets that cross Earth's orbit ($q < 1$ AU), *or* those that do not ($q > 1$ AU). The outcome could be sensitive to "Jupiter's" mass.
- As the mass of Jupiter rises, so does the size of the region around the planet through which a passing comet will experience significant orbital perturbation. While this obviously leads to an increase in the ejection rate of comets, it will also increase the number that have their orbital period significantly reduced, which could mean that comets get, on average, more opportunity to hit the Earth, prior to being ejected. It is therefore prudent to check whether that effect could counterbalance, or even outweigh, the increased ejection rate caused by a larger Jupiter.

In order to check whether these two effects could in any way alter our results, we carried out a number of further tests (as detailed in our 2010 paper). We first compared the survival rates, as a function of Jupiter mass, for the subsamples of our initial test population that had $q < 1$, 1.524 and 5.203 AU (Earth, Mars and Jupiter-crossing objects respectively). Although it was clear that objects on Jupiter-crossing orbits were ejected more efficiently than those that remained beyond the giant planet's orbit, no preferential survival of Earth- or Mars-crossing orbits was found by comparison to the survival of Jupiter-crossers. In other words, the only distinction lies between those comets that cross Jupiter's orbit and those that do not, and this therefore does not alter our results.

To examine the second possibility, we looked in more depth into the behaviour of Jupiter-crossing objects as a function of time, using them as a proxy for the far less numerous Earth-crossing objects (which, as described above, behave in essentially the same manner as the Jupiter-crossers). Rather than simply considering the number of objects surviving, we calculated instead the probability of the Earth being hit as a function of time (using the number of objects passing perihelion in that time period as a direct proxy). Just as was the case when considering the ejection rate as a proxy, we found that the probability of collision fell away dramatically as a function of time, with the greatest and most rapid falls occurring for the scenarios that featured the most massive Jupiters. Indeed, we found that the mass of Jupiter has only a small effect on the mean orbital period of the cometary bodies – the increased efficiency with which they are ejected from the system as the planet's mass increases is by far the dominant effect, resulting in a significantly reduced threat to the Earth.

As was the case for the Centaurs, the population of long-period comets is continually being replenished by the injection of new members from the Oort cloud. As the mass of Jupiter goes up, the dynamical half-life of the population of injected objects falls (as evidenced by the enhanced ejection rate at higher masses), while the mean orbital period of the objects remains almost unchanged. With a constant flux into the long-period comet population, systems in which the "Jupiter" is more massive (and hence more efficiently ejects comets from the system) would therefore have a smaller population of potentially hazardous long-period comets at any given time, and the impact rate would therefore be reduced accordingly. In other words, when one considers the long-period comet flux (and in contrast to our earlier findings), a more massive Jupiter certainly appears to offer some measureable shielding to the Earth over scenarios in which no such planet is present.

Discussion

Taken as a whole, our results show that the role of a giant planet in Jupiter's orbit in influencing the impact regimes experienced by the Earth is, at the very least, significantly more complicated than had previously been thought. When considering the results of our three suites of integrations, it is important that the reader view them in the context of current thinking on the Earth's current impact regime. Fifty years ago, when impact craters were first being acknowledged as having an extraterrestrial origin, the great bulk of known Earth-crossing objects were long-period comets. Given that Jupiter's role in ejecting these comets was reasonably well established even then, it is only natural that people would come to the conclusion that Jupiter acts to shield the Earth from impacts – if Jupiter were not there, more long-period comets would survive to threaten the Earth, and the impact flux would therefore surely be higher. We believe this is the origin of the myth of "Jupiter – friend".

In recent times, however, the picture has changed considerably. With the advent of new technologies, our knowledge of the population of potentially hazardous objects has greatly improved. Once, very few near-Earth asteroids and short-period comets were known, while these now number in the thousands and hundreds, respectively. With such progress, our understanding of the Earth's current impact regime has also shifted. It is now believed that the near-Earth asteroids constitute at least ~75% of the impact threat our planet experiences, with the short-period and long-period comets combined only contributing at most a quarter (e.g. Chapman and Morrison 1994, Morbidelli *et al.* 2002). However, it should be noted that objects moving on long-period orbits would have typically larger collision velocities, on average, than those on short-period or asteroidal orbits (a result of both their higher inclinations [including retrograde orbits] and greater orbital velocity at 1 AU), which acts to increase the relative importance of the Oort cloud comets as a population of bombarders.

Taken as a whole, our work suggests that, rather than acting as a shield to the Earth, Jupiter instead increases the impact flux our planet experiences over that which would be received if the planet were somehow magically removed from our solar system. The situation would, however, be far worse for the Earth were Jupiter instead reduced in mass to that of Saturn – a scenario that would lead to greatly increased hazard from each of the three populations we considered over the solar system we observe today. Indeed, it is only in the case of comets sourced from the Oort cloud where our results suggest that Jupiter is indeed the friend to the Earth that has long been postulated!

Having said all that, one important caveat to this work is that we have not considered the effect that a smaller (or larger) Jupiter would have on the initial formation of our solar system. The early evolution of our planetary system was undoubtedly highly chaotic (e.g. Gomes *et al.* 2005), and it is quite plausible that, had our Jupiter ceased accretion at, say, the mass of Saturn, then the modern solar system could easily look far different to what we see today. Discussions of the proposed "Late Heavy Bombardment" of the Earth (such as the model put forward by Gomes *et al.* 2005) suggest that both the asteroid belt and the trans-Neptunian populations were severely depleted and sculpted by processes related to the migration and mutual interactions of the forming giant planets. At the same time, the exact origin of the Oort cloud comets, albeit still under some debate, is undoubtedly tied to these same chaotic formation processes. Our work, then, while a useful step along the road to understanding the full nature of the impact threat experienced by telluric worlds in the wider cosmos, still leaves plenty of room for further study.

Conclusions

The idea that the planet Jupiter has acted as an impact shield through the Earth's history is one that is entrenched in planetary science, even though little work had been done to examine this idea. In this work, we detail the results of simulations that reveal that Jupiter's influence is not so straightforward. Indeed, it seems that the presence of Jupiter actually increases the rate at which asteroids and short-period comets impact the Earth. The traditional idea of "Jupiter – the shield" only holds true when one considers the long-period comets, which are so efficiently ejected from the solar system as Jupiter gains in mass that few remain to threaten the Earth. Given that these comets only make up a small fraction of the total impact threat, our startling conclusion is that, overall, Jupiter is not friend but foe!

Interestingly, when it comes to the asteroids and short-period comets, we found that the impact rate does not simply increase with Jupiter's mass. Instead, the flux experienced by Earth is initially low in both cases, when Jupiter has negligible mass, then rises sharply to a peak at around the mass of Saturn, before falling away more gradually thereafter. In the case of the asteroids, this behaviour is the result of variations in the depth, breadth and location of the ν_6 secular resonance in the main asteroid belt, while for the short-period comets it is the result of the interplay between the injection rate of Earth-crossers and the efficiency with which they are removed from the system. Despite the different causes, the similarity between the shapes of the impact distributions is striking. Further work is needed to explore this in more detail.

Future work

We have just started a suite of simulations that will build on this work by examining the effect of variations in the orbital eccentricity and inclination of a Jupiter on the Earth's impact flux. We then intend to move on to studying variations in the architecture of the solar system (the distribution of the planets), building towards a goal of being able to study any exoplanetary systems found to contain an exoEarth. As we discuss elsewhere (Horner and Jones 2010), the first exoEarths should be found in the coming decade, and studies of all the various factors that can determine habitability (of which planetary shielding is no doubt one) will prove crucial in helping to determine which of those planets should be the first to be surveyed in the search for life beyond our solar system. ●

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