A NEW DYNAMICAL MODEL FOR THE LUNAR LATE HEAVY BOMBARDMENT. J. E. Chambers, *NASA Ames Research Center, Mail Stop 245-3, Moffett Field CA, USA, (john@mycenae.arc.nasa.gov)*, J. J. Lissauer, *NASA Ames Research Center, Mail Stop 245-3, Moffett Field CA, USA.*.

Samples of lunar rock returned by the Apollo and Luna missions show a cluster of impact melt ages between about 3.8 and 4.0 billion years (Gyr) ago. Several of the large basins on the moon appear to have formed at aound this time, including Imbrium with a diameter > 1000 km. The lunar highlands which predate Imbrium are covered with smaller craters. Conversely, the lunar maria, which formed more recently than 3.8 Gyr ago, contain relatively few impact craters, and it appears that no large basins have formed within the last 3.8 Gyr. These data have been interpreted in two ways. Either 3.8 Gyr ago marked the end of an era of large impacts which had been declining steadily since the terrestrial planets formed ~ 4.5 Gyr ago. Or there was a sudden increase in the impact rate around 3.9 Gyr ago (sometimes referred to as the "lunar cataclysm"), with relatively quiet periods before and afterwards.

Several dynamical models have been proposed to explain a steadily declining flux of impactors onto the Moon. Wetherill (1975) showed that the last members of a population of leftover planetesimals could survive until the end of the late heavy bombardment. These planetesimals would have had particularly long lifetimes if they moved on orbits that were highly inclined with respect to the planets (Morbidelli *et al.* 2001). Calculations by Evans and Tabachnik (1999) suggest that primordial belts of asteroids located between the orbits of the inner planets could also supply lunar impactors for hundreds of millions of years. Morbidelli and Nesvorny (1999) have shown that main-belt asteroids with weakly unstable orbits would have leaked out of the belt on roughly the same timescale.

Models for a "spike" in the lunar cratering rate are harder to devise since they require that a population of impactors was stored for ~ 600 million years (Myr) after the formation of the Solar System without causing a high rate of impacts in the meantime. One possibility is the collisional breakup of a large main-belt asteroid which would inject many collision fragments into the inner Solar System (Zappala *et al.* 1998). However, to provide enough mass for the late heavy bombardment would require the breakup of a main-belt asteroid $\sim 10\times$ more massive than Ceres (Levison *et al.* 2001), which makes this scenario unlikely.

Alternatively, a large body could have entered the inner Solar System and been tidally disrupted during a close encounter with Earth or Venus (Wetherill 1975). The resuling swarm of debris would have a higher collision probability with the Moon than material in the asteroid belt. Hence, the tidal breakup of a body similar in size to Ceres could account for the lunar cataclysm. However, this would have to be an isolated event. If the body was part of a larger population then other tidal breakups and episodes of heavy cratering would have occurred.

Levison *et al.* (2001) have shown that the late formation of Uranus and Neptune would have displaced large numbers of

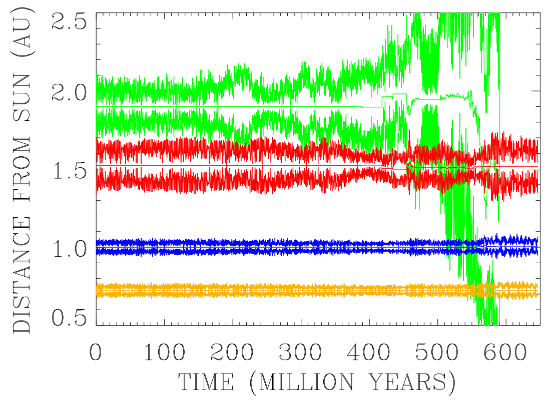

Figure 1: Evolution of the orbits of Venus, Earth, Mars and an additional planet with mass half that of Mars starting on a circular orbit at 1.9 AU. Mercury and the giant planets are included in the integration but not shown. Each set of coloured curves shows perihelion and aphelion distances and semi-major axis for one planet.

small bodies from the outer Solar System and the asteroid belt, causing a lunar cratering spike. In this model, the accretion of Uranus and Neptune was delayed for some 600 Myr, followed by rapid growth to their current masses. This sequence of events is somewhat difficult to reconcile with current models for planetary accretion.

Here we propose a new dynamical model for the lunar late heavy bombardment. We hypothesize that the era of planetary accretion produced a fifth terrestrial planet, *Planet V*, in addition to the 4 inner planets observed today. The extra planet formed on a low-eccentricity orbit that was long-lived but unstable on a timescale ~ 600 Myr. About 3.9 Gyr ago, Planet V was perturbed onto a highly eccentric orbit that crossed the inner asteroid belt. Close encounters with the planet scattered a large fraction of the asteroids into resonances or Mars crossing orbits, temporarily enhancing the population of bodies on Earth crossing orbits and the lunar impact rate. Ultimately, Planet V was lost too, most likely by entering the ν_6 secular resonance (semi-major axis $a = 2.1$ AU) and falling into the Sun.

The temporary existence of more than 4 planet-sized bodies in the inner Solar System is consistent with the currently favoured model for the formation of the Moon. This invokes a collision between Earth and a Mars-sized body 50–100 Myr after the formation of the Solar System (*e.g.* Canup and Asphaug 2001). Rivera (2001) has found that a large proto-lunar impactor could have survived in the region between Venus and Mars for > 200 Myr in many cases. A massive body with a nearly circular orbit between Mars and the asteroid belt will

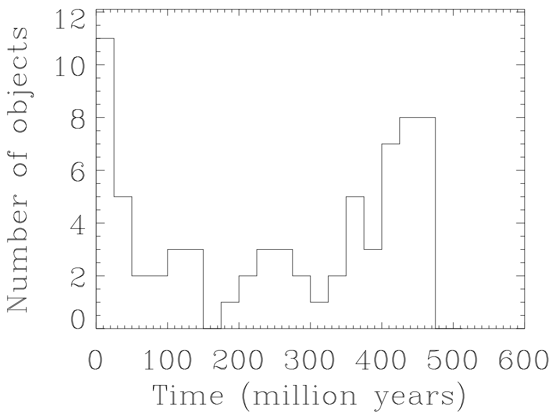

Figure 2: Number of asteroids that evolve onto Earth-crossing orbits versus time for a population of 130 asteroids integrated in the planetary system shown in Figure 1. The asteroids begin with circular orbits with semi-major axes $2.2 < a < 2.7$ AU. The peak in the flux of Earth-crossing asteroids at ~ 400 million years coincides with the time when Planet V first crosses the inner asteroid belt.

have an even longer mean dynamical lifetime since perturbations from Mars are quite weak. In addition, such a body is likely to develop an orbit that crosses the asteroid belt before it is removed. For these reasons, we will focus on the effect of an additional planet with an orbit between Mars and the asteroid belt rather than elsewhere in the inner Solar System.

As a first test of this hypothesis, we have performed 36 N-body integrations of the planetary system (Mercury through Neptune), including an additional terrestrial planet. We set the mass of the planet equal to either 0.25, 0.50 or 1.0 Mars masses, moving on an orbit with semi-major axis $1.8 \leq a \leq 1.9$ AU, and inclination $0 \leq i \leq 30°$. The integrations used a hybrid symplectic integrator (Chambers 1999) with a 7-day stepsize. Each calculation continued until a planet was removed from the system, or 1 Gyr had elapsed.

Figure 1 shows the orbital evolution in one simulation in which Planet V has a mass half as large as Mars, and an initial orbit with $a = 1.9$ AU and $i = 0$. Each set of curves of a particular colour shows the perihelion, semi-major axis and aphelion distances of Venus, Earth, Mars and Planet V respectively. For several hundred Myr, the planets remain on non-crossing orbits, but gravitational perturbations gradually increase the eccentricity e of Planet V until its orbit crosses that of Mars and the inner asteroid belt at ~ 400 Myr. At later times, e and i of Planet V increase rapidly until it enters the ν_6 resonance in the asteroid belt and falls into the Sun at ~ 600 Myr. The orbits of the other terrestrial planets undergo minor changes during this process, with their final a and e similar to their inital values.

The time required for the removal of one planet was generally greatest in simulations in which Planet V began at large heliocentric distances. The geometric mean lifetime $\bar{T}$ was 109, 213 and 420 Myr for $a = 1.8, 1.85$ and 1.9 AU respectively. The geometric mean lifetime also increased with increasing inclination of Planet V up to a maximum of 679 Myr for $i = 15°$. However, in cases with $i = 30°$, $\bar{T}$ was only 64 Myr. In general, systems with a half-Mars-mass Planet V survived longer ($\bar{T} = 377$ Myr) than those with an additional planet of higher or lower mass ($\bar{T} = 170$ and 152 Myr for 0.25 and 1.0 Mars mass bodies).

In systems with a 0.25 Mars mass planet, the most likely outcome was the loss of Planet V by collision with the Sun (7/12 cases). Most of the remaining simulations ended with Planet V colliding with Mars. Since Mars has apparently experienced no giant impacts since its formation, the latter cases can be considered model failures. Conversely, the collision of an additional terrestrial planet with the Sun is not excluded by current observations. For 0.50-Mars-mass planets, the proportion of cases ending with Planet V falling into the Sun was lower (4/12), although in 3/12 of the simulations, the system remained stable for 1 Gyr. In contrast, only 1 simulation with a Mars-mass Planet V ended with its collision with the Sun. Most of these simulations ended in a manner inconsistent with observation (*e.g.* Mars hit Earth, Mercury hit the Sun) Apparently, the presence of a second Mars-mass planet is enough to destabilize the orbits of the other terrestrial planets in most cases.

To examine whether the loss of Planet V can lead to an increase in the lunar cratering rate, we integrated the orbits of 130 test particles in the inner asteroid belt in the planetary system shown in Figure 1. Figure 2 shows the number of asteroids that evolved onto Earth-crossing orbits as a function of time. Following the removal of test particles initially in resonances, the flux of new Earth crossers falls to a low level before increasing again after ~ 400 Myr., This coincides with the time at which the orbit of Planet V begins to cross the asteroid belt. In the final stages of its evolution, Planet V develops a highly inclined orbit and is ineffective at perturbing more test particles into resonances and the flux of new Earth crossing objects falls to zero.

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