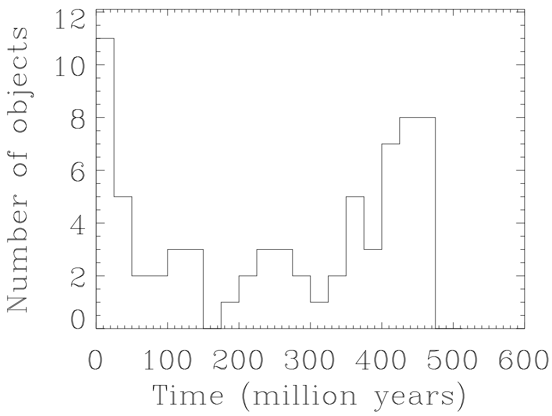

Figure 2: Number of asteroids that evolve onto Earth-crossing orbits versus time for a population of 130 asteroids integrated in the planetary system shown in Figure 1. The asteroids begin with circular orbits with semi-major axes $2.2 < a < 2.7$ AU. The peak in the flux of Earth-crossing asteroids at ~ 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.

References

[1] Canup, R.M. and Asphaug, E. (2001) Nature, **412,** 708–712.

[2] Chambers, J.E. (1999) MNRAS, **304,** 793–799.

[3] Evans, N.W. and Tabachnik, S. (1999) Nature, **399,** 41–43.

[4] Levison, H.F., Dones, L., Chapman, C.R., Stern, S.A., Duncan, M.J. and Zahnle, K. (2001) Icarus, **151,** 286–306.

[5] Morbidelli, A. and Nesvorny, D. (1999) Icarus, **139,** 295–308.

[6] Morbidelli, A., Petit, J-M., Gladman, B. and Chambers, J. (2001) Meteorit ics & Plan. Sci., **36,** 371–380.

[7] Rivera, E. (2001) Ph. D. thesis, SUNY Stony Brook.

[8] Wetherill, G.W. (1975) Proc. 6th Lunar Sci. Conf., 1539–1561.

[9] Zappala, V.A., Cellino, A., Gladman, B.J., Manley, S. and Migliorini, F. (1998) Icarus, **134,** 176–179.