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# Jupiter: Cosmic Jekyll and Hyde

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## Abstract

It has been widely reported that Jupiter has a profound role in shielding the terrestrial planets from comet impacts in the Solar System, and that a jovian planet is a requirement for the evolution of life on Earth. To evaluate whether jovians, in fact, shield habitable planets from impacts (a phenomenon often referred to as the ''Jupiter as shield'' concept), this study simulated the evolution of 10,000 particles in each of the jovian inter-planet gaps for the cases of full-mass and embryo planets for up to 100 My. The results of these simulations predict a number of phenomena that not only discount the ''Jupiter as shield'' concept, they also predict that in a Solar System like ours, large gas giants like Saturn and Jupiter had a different, and potentially even more important, role in the evolution of life on our planet by delivering the volatile-laden material required for the formation of life.

The simulations illustrate that, although all particles occupied ''non-life threatening'' orbits at their onset of the simulations, a significant fraction of the 30,000 particles evolved into Earth-crossing orbits. A comparison of multiple runs with different planetary configurations revealed that Jupiter was responsible for the vast majority of the encounters that ''kicked'' outer planet material into the terrestrial planet region, and that Saturn assisted in the process far more than has previously been acknowledged. Jupiter also tends to ''fix'' the aphelion of planetesimals at its orbit irrespective of their initial starting zones, which has the effect of slowing their passages through the inner Solar System, and thus potentially improving the odds of accretion of cometary material by terrestrial planets. As expected, the simulations indicate that the full-mass planets perturb many objects into the deep outer Solar System, or eject them entirely; however, planetary embryos also did this with surprising efficiency. Finally, the simulations predict that Jupiter's capacity to shield or intercept Earth-bound comets originating in the outer Solar System is poor, and that the importance of jovian planets on the formation of life is not that they act as shields, but rather that they deliver life-enabling volatiles to the terrestrial planets. Key Words: Asteroid—Comets—Interstellar meteorites—Extrasolar terrestrial planets—Simulation. Astrobiology 16, 23–38.


## 1. Introduction

Impact events appear to have had a cosmic ''Jekyll and Hyde'' relationship with life on Earth, as they could have both enabled or extinguished it. Canup and Asphaug (2001) hypothesized that, very early in its history, Earth was struck by an object rivaling the size of Mars. It has been argued that, had that impact (or even multiple large impacts) not occurred and removed a significant fraction of Earth's $CO_2$ budget, our planet would be more likely to resemble Venus, with surface temperatures unable to support liquid water and, hence, life (*e.g.*, Ahrens *et al.*, 2004; Stewart and Mukhopadhyay, 2013; Tucker and Mukhopadhyay, 2014). While the giant impact hypothesis that explains the formation of the Moon has been challenged by a new model (Canup, 2012), impact events are still a necessary part of that scenario.

Another hypothetical early Earth scenario posits a rain of planetesimals impacting a young Earth delivered the volatile compounds necessary for the formation of Earth's hydrosphere (Hartogh *et al.*, 2011), atmosphere, and biosphere (*e.g.*, Thomas *et al.*, 2006). A newer model (Sarafian *et al.*, 2014) suggests, however, that a growing young Earth accreted volatile material from a carbonaceous chondrite source. Though it is widely accepted that the formation and growth of the outer planets occurred before those of the terrestrial planets, the source region of that volatile material may still have been the outer Solar System. In a recent study, Schlichting *et al.* (2015) suggested that impacts by small planetesimals, on the order of 2 km in diameter, represent a competing effect and are the dominant contributors to atmospheric evolution and mass loss over Earth's history.

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Impact events that were capable of sterilizing the planet have occurred throughout its geological history. For example, one of the five major extinction events (Raup and Sepkoski, 1982), the Cretaceous-Paleogene (K-Pg) extinction, was initiated when a 16 km bolide impacted what is today the Yucatan Peninsula near the town of Chicxulub. Originally hypothesized to be an asteroid (Alvarez *et al.*, 1980), more recent analysis suggests that a cometary impactor triggered this mass extinction (Moore and Sharma, 2013). Though many ecosystems at the end of the Cretaceous may have already been under extreme pressure due to large-scale volcanism—particularly due to that which yielded the Deccan Traps flood basalts in modern-day India—the Chicxulub impact remains the most likely cause of the extinction (Renne *et al.*, 2013). In fact, new evidence reinforces the hypothesis that the largest pulse of basaltic outflow from the Deccan Traps, which accounts for upward of 70% of the flow volume, was triggered by the Chicxulub event (Richards *et al.*, 2015). Another of the largest mass extinction events in Earth's history occurred at the Permian-Triassic boundary, known as ''The Great Dying.'' During that extinction, 57% of all families, 83% of all genera, and between 90% and 96% of all species perished (Benton, 2003). The most likely cause for this extinction is attributed to large-scale eruptions of flood basalts. Though an impact trigger is unlikely (Saunders and Reichow, 2009), it has also not been entirely ruled out (Tohvera *et al.*, 2012). For each mass extinction, the bulk of Earth's biosphere required a significant amount of time to recover its pre-extinction diversity, though opportunistic species no doubt thrived on the carnage. For example, it has been estimated that after the Permian-Triassic extinction event, Earth's biosphere took from 10 million (Chen and Benton, 2012) to as much as 30 million (Sahney and Benton, 2008) years to rebound.

If impact events were larger or more frequent, Earth's biosphere might be radically different from today, perhaps even nonexistent. Some have claimed that Jupiter serves in the role as a cosmic shield, dramatically lowering the flux of planetesimals through the inner Solar System. The claim is that this allowed Earth's biosphere to thrive—creating a less hostile environment by lowering the terrestrial impact rate.

Oort cloud comets have inclinations that range from 0 to ±90 degrees. Though many Oort cloud comets on highly inclined orbits pass through the inner Solar System, they never pass near the jovian planets. Jupiter is clearly an ineffective shield against a large fraction of potential Earth-impacting comets of this type.

Long-period comets, however, are not the greatest impact risk. Short-period comets—those with inclinations closer to the ecliptic—have much higher likelihoods of impacting terrestrial planets. How Jupiter shields the inner Solar System from this threat is less obvious.

### *1.1. The origin of the "Jupiter as shield" paradigm*

Though now widespread, the origin of the ''Jupiter as shield'' paradigm is murky. Horner and Jones (2008a, 2008b) noted: ''The idea that a giant planet is required beyond the orbit of a terrestrial one, in order that a planet be habitable, is well entrenched in the astronomical community… It is hard to find the origins of the 'Jupiter as shield' theory.'' The paradigm was certainly popularized by Ward and Brownlee (2000) in their book *Rare Earth*, and the claim stems from their interpretation of the work of George Wetherill (1994, 1995).

Wetherill postulated that extrasolar jovian planets, which at that time had not yet been detected, may be rare. The absence in the literature at that time of reports of interstellar comets on hyperbolic, or unbound, trajectories—comets that would have been ejected from their systems by jovian planets during the early stage of planet formation—reinforced Wetherill's conjecture that jovian planets may be the exception rather than the rule. Wetherill (1994) noted that building a jovian planet is a race, one in which a planetary core must grow large enough fast enough so that it can capture significant nebular gas before that gas is blown away by the system's star.

To test his hypothesis that extrasolar jovian planets may be rare, Wetherill (1994) performed a series of five different types of computational simulations that modeled the evolution of massless test particles in the presence of jovian planets of varying masses. Should the norm be that planetary systems with terrestrial planets evolve with ''failed Jupiters,'' then there should be no reasonable expectation of ever seeing interstellar comets on hyperbolic trajectories. Wetherill noted, ''there are several ways in which Jupiter (and Saturn) may fail to form in systems for which terrestrial planets may occur.''

Wetherill used Monte Carlo techniques to simulate complex Solar System dynamics numerically and employed a series of simplifications and approximations in place of computationally intensive first-principles computations in order to make the best use of the computational resources available at the time. While it may seem unfair to compare computational simulations of today to those of 1994, if the fundamental work underlying the ''Jupiter as shield'' concept had a systematic flaw, then revision of the original work is warranted.

A key and most oft-cited result of the work of Wetherill (1994) was the finding that if Jupiter and Saturn only grew to the size of their cores—to 15 Earth masses—the flux of potentially Earth-impacting planetesimal material would be 1000 times what it is today. The significance of this result is not that Jupiter shields Earth against inbound impactors, but rather that Jupiter helps rid the the inter-planet gap reservoirs of leftover planetesimal material. In fact, previous studies (*e.g.*, Gladman and Duncan, 1990; Holman and Wisdom, 1993; Grazier *et al.*, 1999a, 1999b) have examined the lifetime of planetesimals orbiting in the gaps between the jovian planets and arrived at the same conclusion: planetesimals in these gaps have very short lifetimes relative to the age of the Solar System. Echoing these studies, Ward and Brownlee (2000) stated,

> In the early solar system, there were tremendous numbers of small bodies that had escaped incorporation into planets, but over half a billion years, most of the larger ones inside the orbit of Saturn disappeared. They were accreted by planets, ejected out of the solar system, or incorporated into the Oort cloud of comets. Jupiter was the major cause of this purging…

The authors also claimed, ''Because it cleans our solar system of dangerous Earth-orbit-crossing asteroids and comets, Jupiter has a beneficial influence on life on Earth.'' Rather than suggesting that Jupiter had an important role in purging the outer Solar System of the last vestiges of planetesimal material, this statement suggests that Jupiter shields Earth from objects already on Earth-crossing trajectories.

The study by Wetherill (1994) contains only one reference that might be interpreted to mean that Jupiter has a role in shielding the inner Solar System in this manner. In regard to simulations where the jovian planets had acquired masses significantly less than what they have presently—what Wetherill called ''failed Jupiters''—he stated that the reduced masses would have ''the effective removal of the 'Jupiter Barrier' that must be penetrated by both Oort cloud and Kuiper belt comets if they are to achieve Earth-crossing orbits.'' In the field of planetary dynamics, the connotation of the term ''Jupiter barrier'' (*e.g.*, Levison *et al.*, 2001) is that Jupiter is less of an impenetrable shield and more of a dynamical filter or ''membrane.'' In a follow-up paper, Wetherill (1995) concluded, ''more easily made terrestrial planet systems physically similar to ours may be abundant but hazardous unless protected by gas giant planets.'' Out of context, this sounds like Wetherill also argues in favor of Jupiter's role as a shield, but the claim was made in reference to Jupiter's role in the final planetesimal purge.

Ward and Brownlee's interpretation of Wetherill's work led them to further suggest that the presence of a large jovian planet in a superior orbit is a practical requirement for the evolution of life on a terrestrial planet: ''When planetary systems lack a Jovian planet to guard the outer boundary of the terrestrial planet region, the inner planets may not be capable of supporting more than microbial life'' (Ward and Brownlee, 2000).

This extrasolar variation on the ''Jupiter as cosmic shield'' concept was accepted by the astronomical community with little critical examination, despite the fact that a growing string of papers raised serious concerns regarding its validity. This paradigm also overlooked the possibility that the jovian planets may be the reason many objects collided with Earth in the first place. This would have presented a conundrum: objects from the outer Solar System have high concentrations of the volatile compounds required for life, and impacts with Earth may help explain the current composition of its hydrosphere and atmosphere.

Grazier *et al.* (1999a) began the succession of research that led to the current efforts by searching for potential reservoirs of planetesimal material in the outer Solar System. The authors simulated the trajectories of 100,000 particles in the Jupiter/Saturn gap for up to 1 Gy. Particles were removed from the simulation upon entry into the sphere of influence of one of the jovian planets. Even though planet/planetesimal close approaches were not modeled, only 1.7% of the particles finished those simulations on eccentric orbits with semimajor axes interior to Jupiter.

Laakso *et al.* (2006) also sought to advance the work of Wetherill (1994) by examining the lifetimes of particles already on Earth-crossing orbits in the presence of different jovian planet configurations. The results of these simulations indicated that, as the mass of Jupiter was increased, the rate at which particles were perturbed out of planet-crossing orbits also increased, though the correlation of that rate with the variation in the position of Jupiter was weak.

Grazier *et al.* (2007) then performed a 12 My integration of 10,000 particles in each of the inter-planet gaps to explore the evolution of planetesimals from the Centaur region into the scattered disk—the distant region of a Solar System sparsely populated by icy minor planets. These integrations, which did simulate close planet/planetesimal encounters, revealed that, for particles initially situated between Jupiter and Saturn, 24% had single encounters with jovian planets that propelled them into Mars-crossing orbits. From the Saturn/Uranus region, 15% of particles became Mars-crossers, along with 3% for those from the Uranus/Neptune region (the values were 10%, 6%, and 3%, respectively, for Earth-crossers). That study did not track whether those particles actually made it to the inner Solar System. Grazier *et al.* (2008) performed a more thorough mining/analysis of the same simulation output and found that the overwhelming majority of those encounters resulted in terrestrial planet crossings. They concluded from those, ''In our simulations Jupiter was, in fact, responsible for the vast majority of the encounters that kicked outer planet material into the terrestrial planet region. Our simulation suggests that instead of shielding the terrestrial planets, Jupiter was, in fact, taking 'pot shots.'''

A series of papers by Horner and coauthors (Horner and Jones, 2008a, 2008b, 2009, 2013; Horner *et al.*, 2010), under the collective title ''Jupiter: Friend or Foe?'', reported on Jupiter's ability to shield the terrestrial planets from asteroids, Centaur objects, and Oort cloud comets. Horner and Jones (2008a) found that, as a result of resonant interactions, Jupiter will perturb planetesimals situated between the orbits of Mars and Jupiter into the inner Solar System, and that the absence of Jupiter can protect the terrestrial planets more than a Jupiter having any of a range of masses. Most relevant to the Wetherill (1994) study and this work, Horner and Jones (2009) found that, for Centaur objects, the existence of a Jupiter provides little shielding for the inner planets and can, in fact, significantly increase the flux of impactors through the terrestrial planet region. Horner *et al.* (2010) demonstrated that Jupiter provides some degree of terrestrial planet shielding from Oort cloud comets, and more massive ''Jupiters'' provided greater shielding.

In a comparatively brief series of simulations that attempted to quantify the composition and source regions of Ceres' ices, Grazier *et al.* (2014) integrated the trajectories of 2000 particles in each of the inter-planet reservoirs for up to 5 My. The fraction of icy planetesimals that pass through the Asteroid Belt, potentially delivering volatile material to Ceres and other ''wet'' asteroids in that time, was significant; and in those simulations, planetesimals originating from the Jupiter/Saturn zone were orders of magnitude more abundant than those originating from the Uranus/Neptune reservoir when the planets were just embryos. In that study, significant quantities of outer Solar System particles were delivered to the terrestrial planet region.

Here we report the results of a series of simulations that were a continuation of, and complementary to, our previous work (Grazier *et al.*, 1999a, 1999b, 2007, 2008, 2014). Using our Solar System as a test bed, we performed highly accurate numerical integration techniques that simulated the trajectories and tracked the orbital evolutions of 30,000 particles on low-eccentricity low-inclination orbits situated initially between Jupiter and Neptune in the presence of both full-mass jovian planets and jovian cores or embryos (note that the planetary cores that Wetherill referred to as ''failed Jupiters'' will be referred to here synonymously as planetary ''embryos''). Here, the initial conditions and modeling approach are presented in Section 2, based largely upon previous work by Grazier *et al.* (1999a, 1999b, 2005a, 2005b). Results that track the fate of planetesimals orbiting in the outer Solar System in the presence of full-mass jovian planets and embryos are presented in Section 3. Finally, in Section 4, the implications of these simulations are presented along with a reflection on their relevance to the ''Jupiter as shield'' hypothesis.

The simulations indicated that, although Jupiter does a very poor job of shielding Earth from potential impactors early in the history of our Solar System, it played a key role in injecting substantial quantities of material from the outer to the inner Solar System. Whether through resonant interactions, close planet/planetesimal encounters, or a combination, the simulations indicate that a significant number of non-Earth-threatening objects initially situated in the outer Solar System could evolve to pass through the terrestrial planet region. Jupiter, rather than shielding the terrestrial planets, contributed to the vast majority of encounters that redirected planetesimals inward, yet the degree to which Jupiter relied upon Saturn's assistance to do this has not been recognized, and the current simulations illustrate the incredible complexity of planetesimal evolution in the early Solar System.

Although Jupiter may very well have had a beneficial influence for life on Earth, it is not because it acted as a shield against comets but rather because it helped bombard the inner Solar System with volatile-laden planetesimals and may have helped Earth accrete its atmosphere and hydrosphere. Importantly, these conclusions are not only germane to our Solar System but assume a greater significance when we use our Solar System as a proxy for extrasolar planetary systems. In fact, a key result of this work is an improved ability to identify planetary system configurations that are more propitious for volatile enrichment of Earth-like planets.

## 2. Integration Method and Initial Conditions

In Wetherill's (1994) work, he performed five different types of simulations of trajectories of thousands of planetesimals in the presence of jovian planets: simulations with the full-mass jovian planets of today, with 15 Earth-mass ''failed Jupiters,'' with 1 Earth-mass cores of Uranus and Neptune, with Saturn-sized Uranus and Neptune, and with a highly eccentric Jupiter.

To establish rigorously whether Jupiter is an effective planetesimal shield for the inner Solar System, simulations similar to Wetherill's were performed using highly accurate numerical techniques, building upon our previous work (Grazier *et al.*, 2007, 2008, 2014). Eight different sets of simulations were conducted that fall into three categories.

For the first two categories of simulations, the trajectories of 10,000 massless particles in each of the jovian planet and jovian embryo inter-planet gaps were simulated for up to $10^8$ years. The inter-planet gaps, the Jupiter/Saturn, Saturn/Uranus, and Uranus/Neptune zones, are referred to hereafter as J/S, S/U, and U/N zones, respectively. These simulations allowed us to perform direct comparisons to the most important three of the five of Wetherill's simulations: simulations with the full-mass jovian planets of today, with 15 Earth-mass ''failed Jupiters,'' and with 1 Earth-mass cores of Uranus and Neptune (Wetherill, 1994). Note that we did not attempt direct comparisons with Wetherill's simulation of enhanced-mass ice giants or his simulation of Jupiter on an eccentric orbit. The role of Earth-mass Uranus and Neptune can, in important respects, be examined more thoroughly when coupled with embryos for Jupiter and Saturn, because when these planets are simulated using their full masses, they efficiently and rapidly eject planetesimals from the simulations—oftentimes without even close approaches (Grazier *et al.*, 1999a, 1999b, Horner *et al.*, 2010).

The third category of simulation was run to assess the comparative roles of Jupiter and Saturn in shielding the inner Solar System, delivering material to the inner Solar System, and depleting the outer Solar System of planetesimals. Using present-day masses, we simulated $10^4$ particles interior to Saturn but without Jupiter (hereafter called SNJ for ''Saturn no Jupiter'') and another $2\times10^4$ particle simulation without Saturn (hereafter called JNS for ''Jupiter no Saturn''). The particle count was doubled in the JNS simulations because the J/U zone has the combined volume of the J/S and S/U zones from the other simulations. The reader is referred to the Supplementary Material (available online at www.liebertonline.com/ast) for an examination of the stability of these hypothetical planetary systems.

In these simulations, the Sun and planets were mutually interacting, while the planetesimals were massless and influenced by only the Sun and jovian planets. Initial planet *GM* values were extracted from JPL Ephemeris DE 245. The masses of the inner planets were added to that of the Sun in all simulations. Initial masses for Jupiter embryos (Wetherill, 1994; Nettelman, 2011) and Saturn embryos (Wetherill, 1994; Hubbard *et al.*, 2008) were 15 Earth masses, while those for both Uranus and Neptune were 1 Earth mass (Wetherill, 1994; Helled *et al.*, 2011). Initial planet positions for all three categories of the simulations were also taken from JPL Ephemeris DE 245.

For the initial particle orbits in each inter-planet gap, the particle semimajor axes were chosen from a normal distribution with mean equal to the average of the semimajor axes of the adjoining planets, and the $3\sigma$ points to coincide with the semimajor axes of the neighboring planets. Particle inclinations were distributed normally, with mean 0 degrees and standard deviation 5 degrees (prograde orbits only). The eccentricities were chosen randomly, between 0 and 1, from a negative exponential distribution with an e-folding constant of 0.1. The other orbital elements ranged from 0 to 360 degrees and were chosen from uniform distributions. For a full description of the initial particle distribution, see Grazier *et al.* (1999a, 1999b).

The particle distribution for the SNJ runs was the same as that for the J/S simulations. Although it could be argued that a uniform distribution is more pertinent in this case, since Jupiter and Saturn are in near resonance, Saturn effectively and rapidly perturbs particles orbiting near Jupiter's semimajor axis into different orbits, so this region would quickly become depleted anyway. The distribution in the JNS runs was selected such that the peak of the semimajor axis distribution was at the midpoint of the J/U zone.

To integrate planet and planetesimal trajectories, we employed a method of integration originally due to the work of Störmer (1907). Our implementation is a truncation-error-controlled, $13^{th}$ order, modified Störmer integrator that employs a roundoff error minimization scheme we call ''significance-ordered computation.'' Details of our implementation can be found in the work of Grazier *et al.* (2005a, 2005b). Our time step was 1/1024$^{th}$ of Jupiter's period (4.24 days), selected to minimize roundoff error, and "tuned" to the order of the method to ensure stability. The reader is referred to the Supplementary Material for integrator error growth tests.

The simulations on which we report do not take into account the role that jovian planetary migration may have had on the evolution of particles in the inter-planet gaps. There is no universal agreement upon the distance that the jovian planets migrated, or even the direction—with some results suggesting the jovians migrated inward (Franklin *et al.*, 2004; Li *et al.*, 2011), some outward (Gomes *et al.*, 2005), some both (Walsh *et al.*, 2011). Some of the results of these recent studies are mutually exclusive. We also ignored the effect of nongravitational forces, like solar radiation pressure and gas drag. While the full-mass runs simulated the Solar System of today, for the "failed Jupiter" scenarios of Wetherill, the assumption of the model was that the nebular gas had been blown away before the embryonic jovian planets could accrete appreciable amounts.

Though the dynamics of planetesimal evolution in the presence of the jovian planets is dictated, in part, by resonant effects, the primary influence is close planet/planetesimal encounters. Our integrator uses a time step–varying approach to handle these close approaches based upon our modified Störmer methodology (Grazier *et al.*, 2013).

The code signals a close encounter whenever a planetesimal enters the gravitational sphere of influence of a planet, the radius of which, $r_{soi}$, is defined as

$$r_{soi} = a_{planet}\left(\frac{GM_{planet}}{GM_{sun}}\right)^{2/5}$$

where $a_{planet}$ is the semimajor axis of the planet involved in the encounter, $GM_{planet}$ is the mass of the planet times the gravitational constant, and $GM_{sun}$ is that value for Sol (Danby, 1988).

In the instance of a close encounter, the simulation code stores heliocentric state vectors—positions and velocities from which orbital elements are easily calculated—for the planetesimal as well as all the massive objects in the simulation. The code stores the heliocentric state vector for the planetesimal alone upon exit from the sphere of influence. Planetesimals are removed from the simulations by colliding with the Sun or jovian planets, or when they are ejected from the Solar System (Grazier *et al.*, 2013). By storing planetesimal entry and exit state vectors for each close encounter, encounters with "interesting" behaviors can readily be re-integrated, examined, even visualized, in closer detail. Coupled with both planet and planetesimal state vectors stored at regular intervals, we are able to mine the output for all manner of information: we are able to display the entire orbital history of any particle—or statistics of ensembles—over the entire simulation.

Planetesimals are terminated from the simulations by colliding with the Sun or jovian planets, or when they are ejected from the Solar System (Grazier *et al.*, 2013). For a particle to be considered "ejected" from the Solar System in our simulations, it must meet three criteria: it must have positive energy relative to the Solar System, it must be beyond 50 AU from the Sun, and it must be on an outbound trajectory.

Once a particle's heliocentric distance passes interior to 3.5 AU, the code calculates the dot product of the radius and velocity vectors at every step. When this value changes signs from negative to positive (*i.e.*, the particle has transitioned from inbound to outbound and has just passed perihelion), the simulation code calculates its heliocentric distance. This allows us to track the number of total inner Solar System perihelion passages, as well as how many, and which, particles evolved to the inner Solar System.

In combination, these simulations allowed us to examine (i) key aspects of Wetherill's (1994) conclusions, (ii) Jupiter's efficiency as a defender of the terrestrial planets from comets, and (iii) the role of Jupiter and Saturn in delivering material to the inner and outer Solar System. We also examined how Jupiter may have served the role of "gatekeeper" to the terrestrial planet region and may have aided Earth in accreting life-giving volatile materials delivered from the distant outer Solar System.

## 3. Results

### 3.1. Wetherill's simulations and the Öpik method

Wetherill (1994) assumed that planetesimals were on Keplerian orbits except when they underwent planetary close approaches, an assumption that failed to capture the important influence of resonant effects. To simulate close planet/planetesimal approaches, Wetherill employed a scheme known as Öpik's approximation (Öpik 1951, 1976). Öpik's close approach method assumes that all close encounters are hyperbolic, single-pass encounters. Our simulations, however, often revealed close encounters that displayed much more complicated behavior. Some particles were accreted by the planets, some became bound temporarily, and some were even temporarily captured into orbits for long time periods, before they impacted the planet like D/Shoemaker-Levy 9.

Öpik's close approach method has a singularity in situations when both planet and particle are on parallel trajectories, a situation that arises when the close encounter occurs near the particle's perihelion or aphelion. For very close encounters of this nature, even when Öpik's method does not encounter the singularity, the closer the trajectories are to parallel, the more inaccurate the method becomes (Rickman *et al.*, 2014). Planetary close approaches can cause one apse of a planetesimal orbit to become fixed at that planet's heliocentric distance, meaning subsequent encounters with that planet occur when they are on nearly parallel trajectories.

The circumstances leading to this failure mode are achieved often—for an unacceptably large fraction of the simulated particles—in a long simulation such as Wetherill's and ours. By the end of $10^8$ years of simulation time for the three full-mass zone runs, our close encounter database had over 2.6 million entries that spanned all three inter-planet gaps. Figure 1 shows the inbound perihelion distance plotted against the outbound perihelion distance (blue) and the inbound aphelion distance plotted against the outbound aphelion distance (black) for every encounter with each jovian planet (four planets), for each inter-planet gap simulation (three zones), for particles that survived the encounter. Each point, therefore, represents an event as opposed to a particle, and each event that falls on the vertical red line in each graph represents an event that had a high likelihood of meeting the conditions of the known failure mode of Öpik's close approach method.

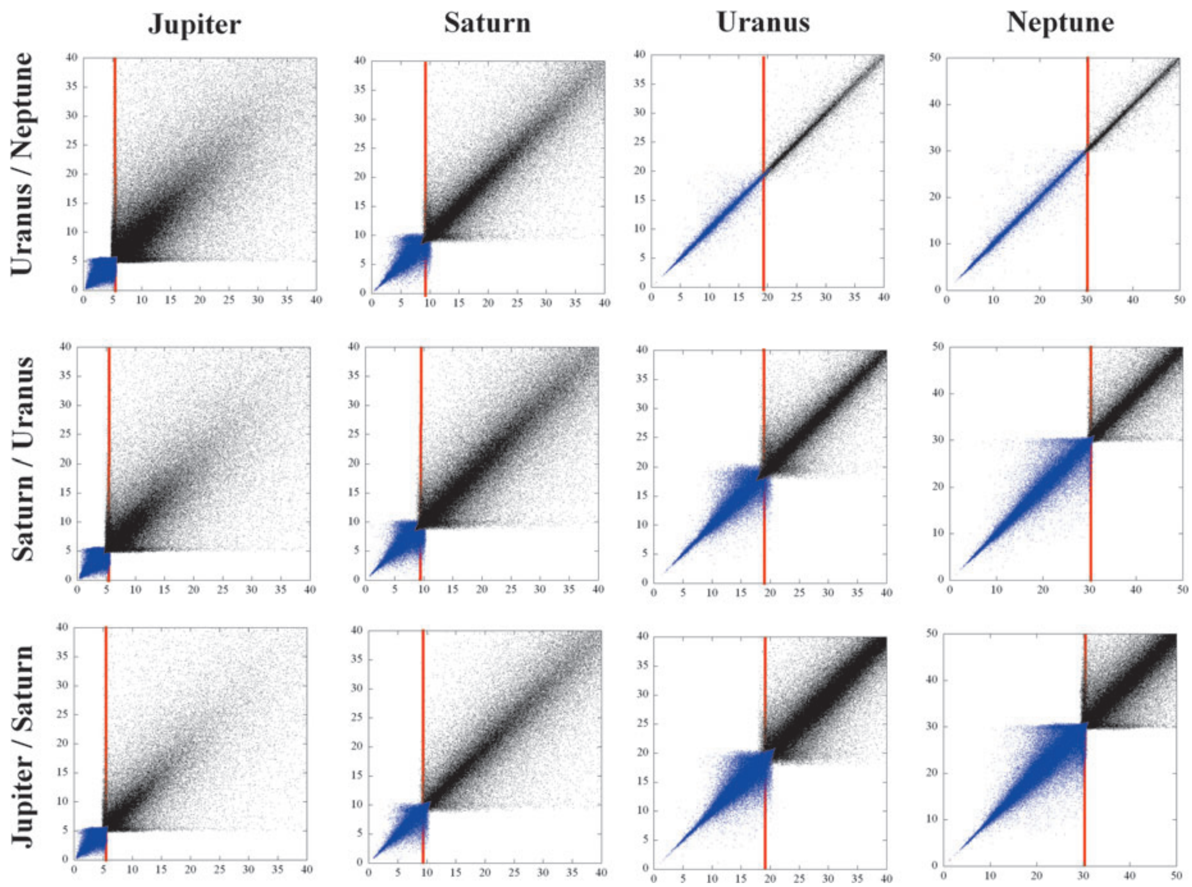


**FIG. 1.** Plot of the inbound vs. outbound perihelion distance (blue) and inbound vs. outbound aphelion distance (black) of the orbits of the particles for every close encounter in our full-mass simulations. Events that fall on the vertical red lines represent failures of the Öpik close approach method. (Color graphics available at www.liebertonline.com/ast)

Table 1 shows the total number of times particles in both full-mass and planetary embryo simulations had close approaches where one apse of the particle orbit was within 0.05 AU of the planet's instantaneous position. We define these events as ''Öpik failures'' since, under these circumstances, the method is inaccurate at best (Newman *et al.*, 2015). Table 1 displays the total number of particles with Öpik failures at perihelion for close approaches to any planet and at aphelion, with column 3 displaying the union of columns 1 and 2—the total number of particles that ever had an Öpik failure at either apse. For particles in the full-mass simulations (initially distributed across all three source regions), for close approaches to any planet, 20,503 out of 30,000 particles (68%) met the 0.05 AU close-approach failure criterion at some point in time over a 100 My simulation. In the planetary embryo simulations, 18,880 of 30,000 particles (63%) met this criterion.

Wetherill's simulations ran approximately 45 times longer than ours, and the sphere of influence he used, which triggered the Öpik close-approach code, was slightly larger

Table 1. The Number of Particles in Each Starting Zone (out of 10,000) That Ever Experienced Öpik Failures at Perihelion and Aphelion over the Course of the 100 My Simulations

| *Zone* | *Total particles with perihelion failures* | *Total particles with aphelion failures* | *Total particles with Öpik failures* |
|---|---|---|---|
| Jupiter/Saturn | 6686 | 4425 | 7575 |
| Saturn/Uranus | 6560 | 3320 | 7126 |
| Uranus/Neptune | 5443 | 2096 | 5802 |
| Jupiter/Saturn embryo | 6033 | 4146 | 6656 |
| Saturn/Uranus embryo | 5938 | 3561 | 6614 |
| Uranus/Neptune embryo | 5232 | 1539 | 5610 |

Column 3 is the union of populations of column 1 and column 2.

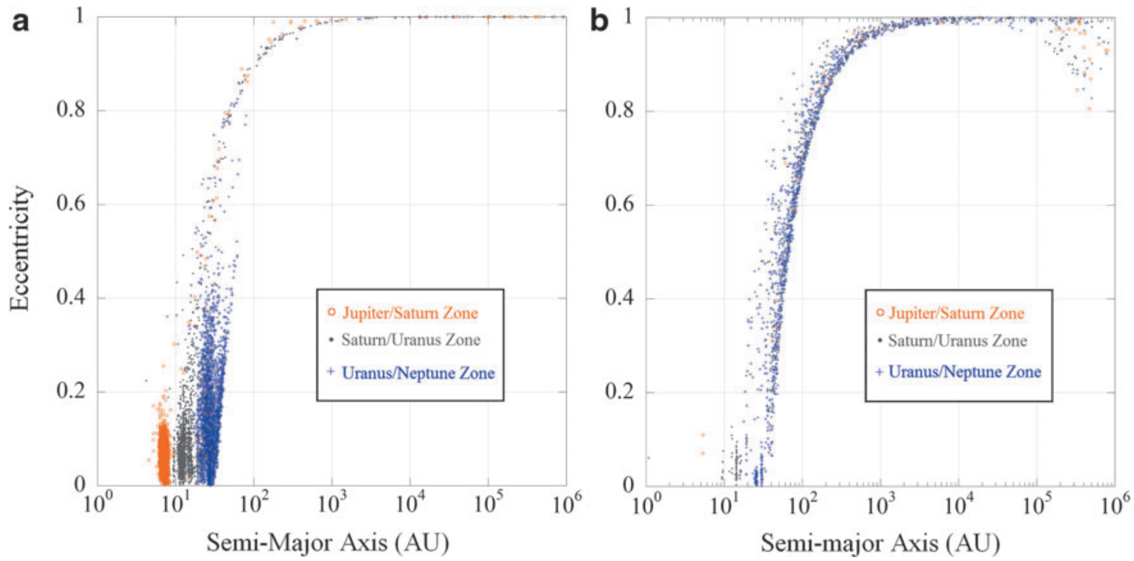


**FIG. 2.** The semimajor axes and eccentricities for all particles that survived 100 My of integration time for both (**a**) planetary embryo and (**b**) full-mass simulations. (Color graphics available at www.liebertonline.com/ast)

than that used in our simulations. It is likely that the failure rate in that study was even higher than was ours. Dones *et al.* (1999) concluded that Öpik's method overestimates median particle lifetimes by a factor of between 2 and 6. The validity of Öpik's close approach code has recently been reevaluated (Newman *et al.*, 2015).

### *3.2. Planetesimal swarm evolution and fates*

Collectively, Figs. 2, 3, and 4 detail the evolution of the particles in all eight simulations over 100 My. Consistent with the work of Wetherill (1994), fully formed jovian planets cleared out reservoirs of material in the inner-planet gaps in the outer Solar System, and most particles were terminated within 5 My (J/S) to 20 My (U/N). As was the case with previous simulations, this finding remains true even when close encounters are not modeled (Grazier, 1999a, 1999b).

Particles remained at the end of all simulations, consistent with our previous studies (Grazier *et al.*, 1999a, 1999b, 2014). Figure 2 shows the semimajor axes and eccentricities of all particles that survived 100 My for both planetary embryo and full-mass integrations. Though many objects remained in orbits between the embryo jovian planets, the few remaining objects in the full-mass simulations interior to Neptune were Jupiter, Uranus, or Neptune co-orbiters. In both full-mass and planetary embryo simulations, many of the surviving particles were cast into the outer Solar System—most of those remaining at the end of the full-mass runs were on highly eccentric orbits. Some were kicked out to extreme distances.

Figure 3 illustrates the ultimate fate of all the particles from our simulations: the percentages of particles that remained in the simulation, those accreted by the Sun or a planet, and those ejected from the Solar System entirely. Among those

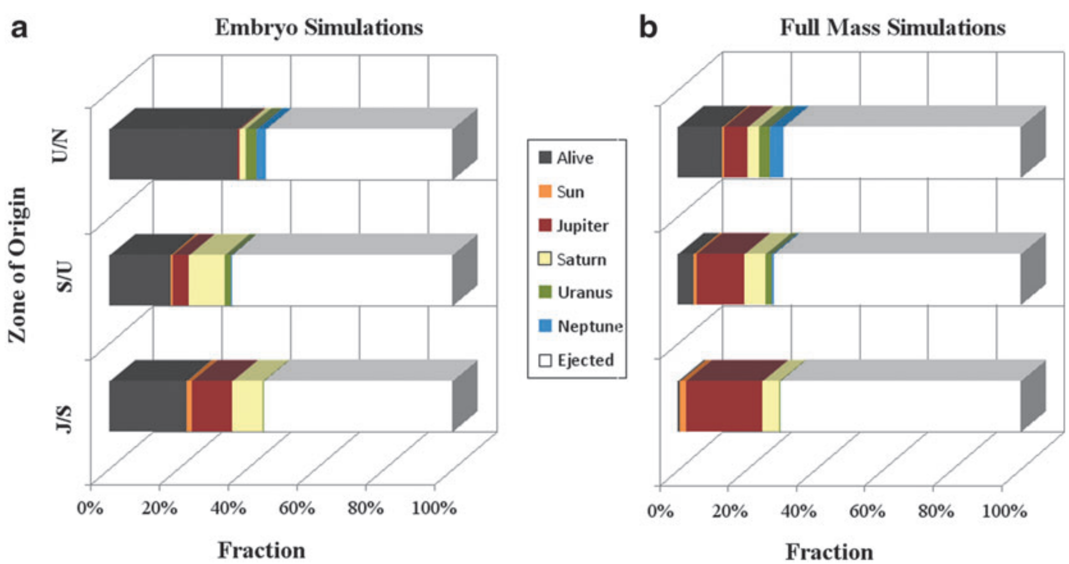


**FIG. 3.** Particle fates after 100 My for both (**a**) planetary embryo and (**b**) full-mass planet simulations, initially with 10,000 particles per zone. (Color graphics available at www.liebertonline.com/ast)

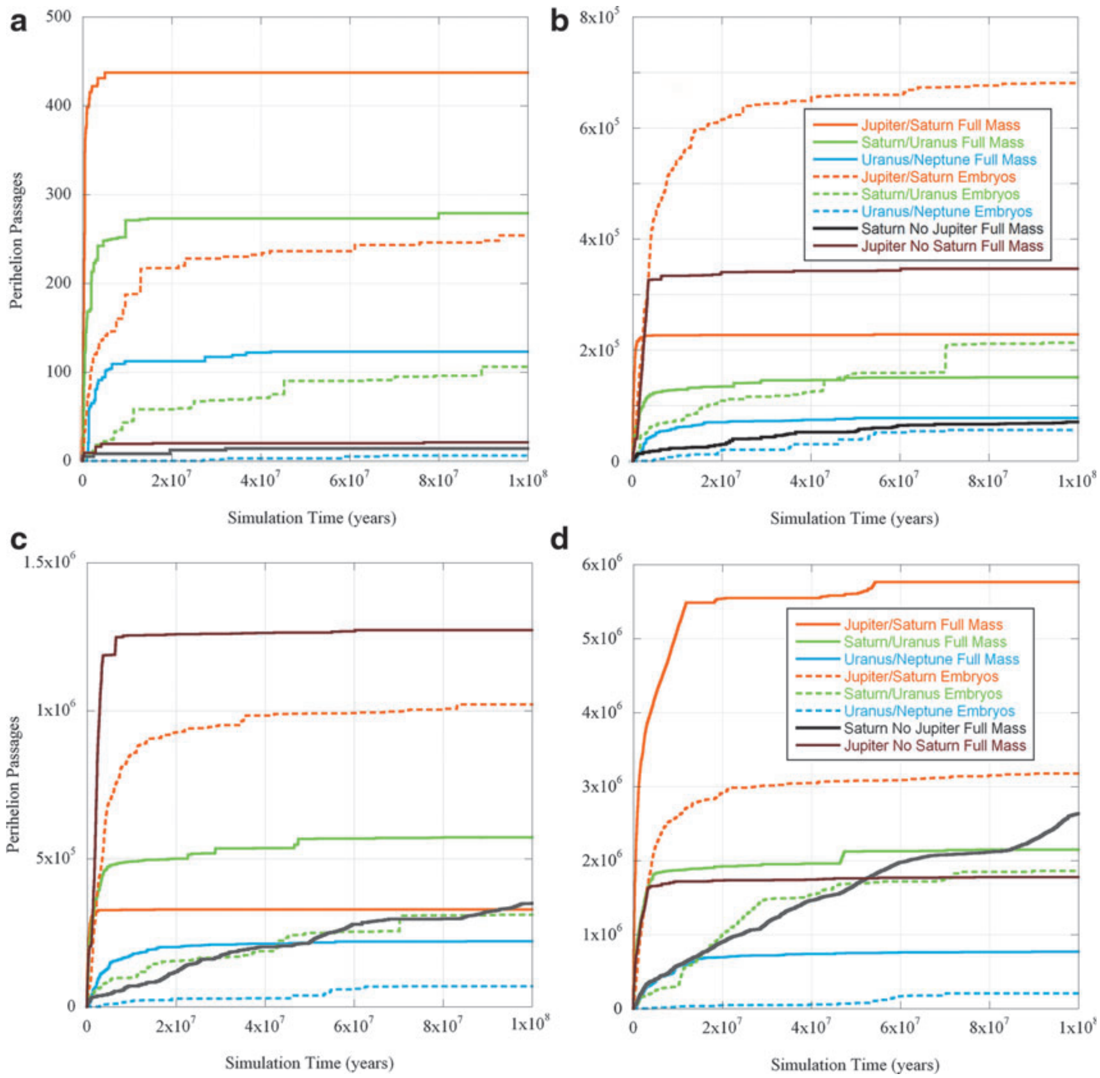


**FIG. 4.** The cumulative number of planetesimal perihelion passages through the inner Solar System as a function of time for all eight different simulations for (**a**) Mercury crossers, (**b**) Venus zone crossers, (**c**) Earth zone crossers, and (**d**) Mars zone crossers. (Color graphics available at www.liebertonline.com/ast)

that were terminated, the number of particles completely ejected from the Solar System was far greater than those that were accreted by the Sun or jovian planets for all zones. Both full-mass and planetary embryo simulations readily ejected particles from the system. In the full-mass simulations, 70% of particles originating in all three reservoirs were ejected; in the embryo simulations, 58% were ejected.

### *3.3. Delivery of planetesimals to the inner Solar System*

Figure 4 shows the cumulative number of times that planetesimals passed through the inner Solar System—with perihelia situated between the orbits of terrestrial planets—as a function of both time and starting zone. Here, perihelion passages were classified according to the inter-planet gap in which they fell. A particle whose perihelion distance fell between the semimajor axes of Mercury and Venus was classified solely as a Venus-crosser and not also counted as an Earth- and Mars-crosser. This is the same criterion used in columns 1, 2, 3, and 5 in Table 2, which reports the number of passages through each terrestrial planet gap, the number of individual particles that ever passed through these gaps, and the average number of passes per particle. Columns 4 and 6 of Table 2 list the same value for all planet crossings. In this instance, a particle with a perihelion passage interior to Mercury *would* also be counted as a Mars-crosser. Column 4 is simply the union of columns 1 through 3. Column 6 is the union of columns 1 through 3 and column 5, the sum total of Mars-crossers or the total number of particles that ever pass into the terrestrial planet region. The rationale for this delineation is that an object with a perihelion passage in column 3 would have a comparatively low impact velocity with Earth and is more likely to be an accretional impact rather than erosional, while an impact into Earth of an object whose perihelion lies interior to an inferior planet (the difference between the values of the two columns) is more likely to be erosional.

The number of planetesimal terrestrial planet crossings as a function of initial zone of origin is complex and often counter-intuitive. Also seen in a previous study (Grazier *et al.*, 2014), there were more Earth crossings in the full-mass

Table 2. Output Displayed as a Function of Simulation Type and Inter-Planet Zone of Origin Include the Number of Unique Particles, Passes, and Average Number of Passes per Particle of Objects Kicked into Orbits with Perihelia Interior to Mercury, between Mercury and Venus, between Venus and Earth, All Earth-Crossers, between Earth and Mars, and All Mars-Crossers

| *Unique particles* | *Mercury zone* | *Venus zone* | *Earth zone* | *Earth crossers* | *Mars zone* | *Mars crossers* |
|---|---|---|---|---|---|---|
| J/S | 96 | 629 | 1,199 | 1,209 | 2,787 | 2,791 |
| S/U | 53 | 400 | 774 | 776 | 1,827 | 1,833 |
| U/N | 28 | 243 | 462 | 468 | 1,024 | 1,028 |
| J/S embryo | 64 | 259 | 284 | 336 | 433 | 487 |
| S/U embryo | 31 | 102 | 114 | 139 | 171 | 205 |
| U/N embryo | 5 | 16 | 16 | 21 | 23 | 28 |
| JNS | 7 | 93 | 207 | 209 | 771 | 774 |
| SNJ | 5 | 51 | 97 | 97 | 261 | 261 |
| *Passes* | *Mercury zone* | *Venus zone* | *Earth zone* | *Earth crossers* | *Mars zone* | *Mars crossers* |
| J/S | 437 | 228,012 | 770,575 | 998,150 | 5,760,898 | 6,759,048 |
| S/U | 279 | 150,872 | 572,390 | 722,983 | 2,147,504 | 2,870,487 |
| U/N | 123 | 77,469 | 221,413 | 298,759 | 768,917 | 1,067,676 |
| J/S embryo | 254 | 681,580 | 1,020,562 | 1,701,888 | 3,175,235 | 4,877,123 |
| S/U embryo | 106 | 212,565 | 310,431 | 522,890 | 1,859,183 | 2,382,073 |
| U/N embryo | 6 | 55,871 | 68,764 | 124,629 | 203,940 | 328,569 |
| JNS | 21 | 346,176 | 1,271,921 | 1,618,076 | 1,775,082 | 3,393,158 |
| SNJ | 14 | 67,181 | 334,764 | 401,931 | 2,542,251 | 2,944,182 |
| *Average passes per particle* | *Mercury zone* | *Venus zone* | *Earth zone* | *Earth crossers* | *Mars zone* | *Mars crossers* |
| J/S | 5 | 362 | 643 | 826 | 2,067 | 2,422 |
| S/U | 5 | 377 | 740 | 932 | 1,175 | 1,566 |
| U/N | 4 | 319 | 479 | 638 | 751 | 1,039 |
| J/S embryo | 4 | 2,632 | 3,594 | 5,065 | 7,333 | 10,015 |
| S/U embryo | 3 | 2,084 | 2,723 | 3,762 | 10,872 | 11,620 |
| U/N embryo | 1 | 3,492 | 4,298 | 5,935 | 8,867 | 11,735 |
| JNS | 3 | 3,722 | 6,145 | 7,742 | 2,302 | 4,384 |
| SNJ | 3 | 1,317 | 3,451 | 4,144 | 9,740 | 11,280 |

simulations by objects originating from within the S/U reservoir than for those from J/S (Fig. 4). Objects originating from within the J/S reservoir pass Jupiter more slowly and are more likely to be swept up into its sphere of influence and potentially accreted or ejected. The next section describes a phenomenon that might have also boosted the S/U zone crossing numbers.

In the case of the S/U and U/N reservoirs, the full-mass simulations generated more terrestrial planet-crossings than did the planetary embryo simulations. For the J/S simulations, though, the planetary embryo simulations resulted in far more Earth and Venus crossings than did their full-mass analog runs. For the three sets of full-mass simulations, 5652 (18.8%) particles had perihelia interior to Mars at some point; for the embryo simulations, only 720 particles from all simulations ever wended their way interior to Mars, and 487 of these originated from the J/S zone. As for potential Earth impactors, 2453 (8.2%) total particles had perihelia interior to Earth at any point in time in the full-mass simulations. For planetary embryo runs, 496 (1.7%) total particles from all three zones ever had perihelia less than 1.0 AU.

For the SNJ simulations, only 261 particles ever evolved into orbits that had perihelia interior to Mars; but once perturbed into the inner Solar System, they typically had a high number of passes per particle (2,944,182 for an average of 11,280 passes per particle). For the JNS simulations, only 774 particles (out of a population of 20,000) reached the terrestrial planet region.

### 3.4. Inner Solar System impact velocities, and accretion of planetesimal material

Based upon the results of a previous study (Grazier *et al.*, 2014), we examined the orbital elements of objects delivered to the inner Solar System. In Fig. 5, the perihelion distance ($q$) is plotted versus the aphelion distance ($Q$) for every inner Solar System passage in our simulation. For the planetary embryo simulations, tendril-like structures in the plots trend from upper left to lower right. Each tendril represents a particle whose orbit, through successive close encounters, became increasingly eccentric—increasing in aphelion distance and decreasing in perihelion distance. Several curves in Fig. 4, particularly those for the planetary embryo simulations, show sharp upticks in the counts of inner planet crossers well into the simulation runs. The explanation for this is shown in Fig. 5. As particles have their perihelia lowered through a series of close encounters, they were classified successively as Mars-crossers, Earth-crossers, Venus-crossers, and Mercury-crossers. Mercury-crossers were often ejected from the Solar System.

Planetary close approaches can cause one apse of a planetesimal orbit to become fixed at the planet's heliocentric

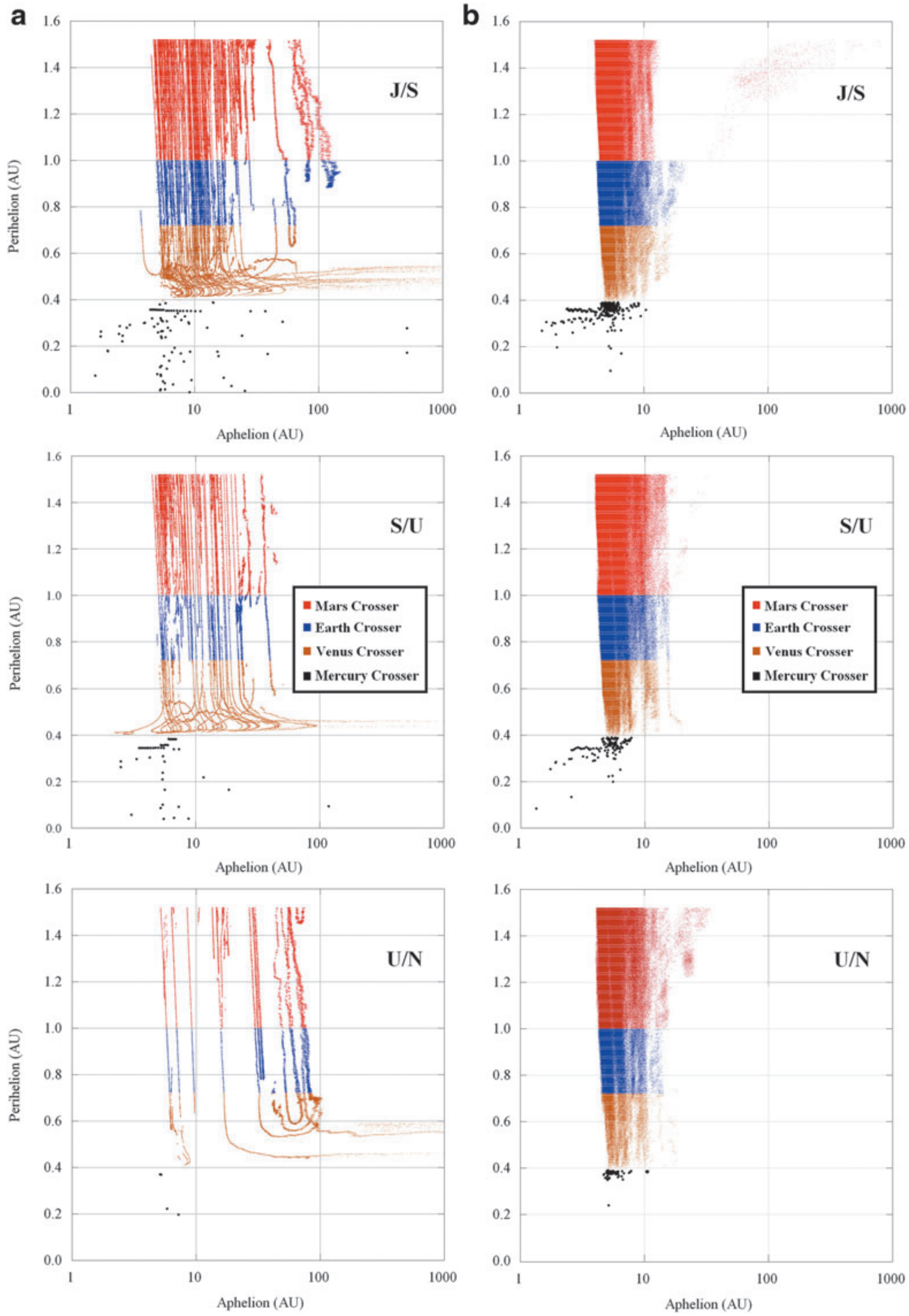


**FIG. 5.** Aphelion distance vs. perihelion distance for particles passing through the inner Solar System ($q < 3.5$ AU) for (**a**) planetary embryo and (**b**) full-mass simulations. (Color graphics available at www.liebertonline.com/ast)

distance. The plots for all three full-mass simulations appear nearly identical, but instead of containing multiple tendrils that correspond to terrestrial planet crossers with aphelia fixed at all the jovian planets, large concentrations of inner Solar System passes resulted for particles having aphelia at 5.2 AU (Jupiter) and, to a smaller extent, $Q = 9.6$ AU (Saturn). Our results show no clusters in aphelia corresponding to the ice giants at 19.2 or 30.1 AU. The V shape of the Jupiter and Saturn clusters in the Fig. 5 full-mass simulation plots simply reflects that it takes a closer planetary flyby to kick a particle nearer to the Sun.

### 3.5. *Testing the "Jupiter as shield" hypothesis*

These simulations allow us to test the concept that Jupiter intercepts or ejects Earth-bound objects approaching from

Table 3. Simulation Results for Total Jupiter and Saturn Encounters with a Number of Different Particles on Cometary Orbits, and the Planets' Shielding Efficiencies

| *Jupiter as a shield* | *Jupiter impact* | *Ejected* | *Tighter orbit* | *Looser orbit* |
|---|---|---|---|---|
| Comet ($Q > 30$) | 7 | 2,700 | 27,775 | 18,284 |
| Comet ($Q > 30$; $q \leq 1$) | 0 | 1 | 7 | 9 |
| Comet ($Q > 100$) | 0 | 2,698 | 5,311 | 2,365 |
| Comet ($Q > 100$; $q \leq 1$) | 0 | 0 | 0 | 0 |
| *Saturn as a shield* | *Saturn impact* | *Ejected* | *Tighter orbit* | *Looser orbit* |
| Comet ($Q > 30$) | 473 | 1,797 | 67,707 | 57,318 |
| Comet ($Q > 30$; $q \leq 1$) | 0 | 0 | 0 | 0 |
| Comet ($Q > 100$) | 97 | 1,231 | 12,192 | 9,553 |
| Comet ($Q > 100$; $q \leq 1$) | 0 | 0 | 0 | 0 |

$Q$ is the value of the planetesimal aphelia in AU, whereas $q$ is the perihelia in AU.

the depths of space. As the simulations progressed, many planetesimals evolved into orbits representative of both short- and long-period comets—with distant aphelia and comparatively small perihelion distances—as displayed in Fig. 2. The objects that evolved to reside on comet-like orbits presented an opportunity to test Jupiter's effectiveness as an inner Solar System comet shield.

Table 3 displays results of every Jupiter and Saturn encounter with a number of different particles on cometary orbits. The first two rows of Table 3 illustrate the fate of objects with aphelia greater than 30 AU that had encounters with Jupiter. From over 48,700 encounters between Jupiter and the comets that evolved from these simulations, 2700 were ejected from the Solar System. Row 3, the subset of row 1 for planetesimal aphelia beyond 100 AU, illustrates that all but two of the ejections reported in Row 1 were objects with very distant aphelia. Rows 6–9 show these same values for Saturn, with similar trends.

Just over half the encounters left the planetesimal involved in the encounter with less energy (column 3)—pulled into a tighter orbit—which is more than the total that were either nudged farther out into the Solar System (column 4) or ejected (column 2). Similarly, 57% of Saturn encounters resulted in planetesimals acquiring more tightly bound orbits, with lower periods than they had pre-encounter. Jupiter accreted only seven objects with aphelia beyond Neptune. While the simulations illustrate that some of the particles that encountered Jupiter could potentially be perturbed into Earth-crossing orbits over time, of the nearly 49,000 encounters between planetesimals whose aphelia reside beyond Neptune, the sum total of Earth-threatening objects that were ejected by Jupiter was 1, and the number intercepted by Jupiter was precisely zero.

## 4. Discussion

One of the most oft-cited results of Wetherill's 1994 paper is that, if Jupiter and Saturn had only ever grown to the size of their core masses—to the approximate size of Uranus and Neptune—then the flux of material through the inner Solar System would be 1000 times higher to the inevitable detriment of Earth's biosphere. Ward and Brownlee (2000) cited this result differently: ''Wetherill claimed, '…if cometary impacts are responsible for a major fraction of Earth's volatile inventory, its volatile content would be much [1000×] larger if gas giant planets were absent.''' This interpretation implies that Wetherill's results were based upon a complete absence of a Jupiter. In both scenarios, the assumption has been that Jupiter alone clears out a reservoir of potential Earth-impacting bodies.

When considered collectively, Figs. 2 through 5 suggest that neither way of viewing Jupiter's role has merit. Had Jupiter and Saturn grown to only 15 Earth masses, the planetary embryo integrations show that embryos, through a series of close planet/planetesimal encounters, can kick a large number of objects into the inner Solar System. These figures also suggest that they still would have cleared their zones of most, or all, unaccreted material and would have created an impact hazard to the inner Solar System at least equal to that of today.

How much credit for this purge belongs to Jupiter? Our SNJ and JNS simulations help clarify Jupiter's role. In these simulations, many particles remained between the bounding planets after 100 My integrations. When these simulations were extended 10 times longer to 1 Gy (data not shown), approximately 40% of the initial SNJ ensemble of particles survived in a belt that ranged from 5.2 to 8.2 AU, along with a lone Saturn co-orbiter. The JNS simulations reported here yielded a planetesimal belt between Jupiter and Uranus from 5.6 to 15.8 AU, which contained approximately 55% of the initial ensemble, along with a handful of Jupiter and Uranus co-orbiters. This finding suggests strongly that, if either Jupiter or Saturn were not present, the Solar System would look quite different.

Based upon many previous studies (*e.g.*, Grazier *et al.*, 1999a, 1999b), it is unsurprising that, in our full-mass simulations, a large number of objects were propelled into the scattered disk, the Oort cloud, or even ejected from the Solar System entirely, many after making multiple passes through the terrestrial planet region.

Wetherill (1994) referred to ejections as a ''leak'' of planetesimals into interstellar space. An important outcome of Wetherill's original work was that the ''leak'' would be far less effective for ''failed Jupiters'' than full-mass planets. Our planetary embryo integrations, the equivalent of Wetherill's failed Jupiters simulations, revealed that planetary embryos were also able to eject a significant fraction of Centaur objects into interstellar space. The output displayed in Figs. 2 and 3 illustrates that even a system populated with planetary embryos is very effective at creating a population of interstellar comets that rivals that of their full-mass counterparts. The simulations suggest that a dearth of interstellar comet observations is uncorrelated with the formation of jovian planets.

From the work of Ward and Brownlee stemmed the notion that, in order to have a habitable Earth-like planet, there should be a jovian planet in a superior orbit to act as a shield against life-ending comet impacts. From the simulation results presented here, one can hypothesize that, although Jupiter may prove to be a questionable shield, a jovian planet may be useful, instead, to deliver necessary life-enabling volatile compounds to the inner Solar System.

Perhaps what previously has not been fully appreciated is that planetesimal reservoirs are fully cleared only by the influences of multiple jovian planets. An examination of the output plotted in Figs. 3 and 5 illustrates that, without Jupiter's perturbing influence, few planetesimals would have impacted Earth. Our JSN and SNJ runs suggest that even that may be insufficient, and it may take two jovian planets, working in concert, to deliver an appreciable amount of volatile material to the terrestrial planet region. Without Jupiter, far fewer objects were ejected from the Solar System; without Saturn, far fewer objects were perturbed into Jupiter's path. Though Jupiter has primarily been credited with clearing of the outer Solar System, Saturn was an important accomplice. To use an analogy from sports: Jupiter may score the goal, but Saturn earns an assist.

As shown in Table 2 and Fig. 5, the mass of the planets versus the embryos has multiple consequences. The full-mass planets propelled a larger number of particles into the inner Solar System than did lower-mass embryos—the same degree of gravitational ''boost'' that a planetesimal receives from a close approach to a full-mass jovian planet requires many such encounters with an embryo. Considering the J/S zone as an example, in the full-mass simulations, 1199 particles made 770,575 Earth crossings (for an average of 643 passes per particle), whereas in the planetary embryo simulations, 284 particles made 1.02 million passes (averaging 3594 passes per particle). A similar outcome held true for the other zones, as revealed in Table 2.

The mass of the planets also affected the resident time of the planetesimal's inner Solar System orbits. In the planetary embryo simulations, once a particle reached an orbit that penetrated the inner Solar System, it remained in that orbit for extended periods of time—often several thousands of perihelia passages (Table 2). The lower masses not only mean that particles took longer to evolve into terrestrial planet-crossing orbits, they take longer to evolve out of them in the planetary embryo simulations.

For those objects with orbits that simultaneously crossed the orbits of both terrestrial and jovian planets, the more massive jovians perturbed the particles out of the terrestrial planet region sooner (similar to the results of Laakso *et al.*, 2006). Horner and Jones (2009) obtained similar results to those found here. In that work, they suggested that a young Jupiter with approximately 60 Earth masses resulted in the maximum number of terrestrial planet crossings and struck a balance between the number of particles kicked into the inner Solar System versus the duration of time those particles remain on terrestrial planet-crossing orbits.

The results of the JNS runs shared important properties with the full-mass simulations, while the SNJ runs behave more like the planetary embryo simulations. With one-third the mass, and at nearly twice the heliocentric distance, Saturn alone injected fewer particles into the inner Solar System than Jupiter alone. Those planetesimals that were injected into the inner Solar System by Saturn did so only after multiple close encounters.

Not only did the bounding planets in either the SNJ or JNS simulations not clear their zones of particles, the SNJ run did not have the same early cascade of terrestrial planet crossings as most other simulations. There were appreciable inner-planet crossings only after the simulations were well underway and the system had time to evolve. The SNJ simulations demonstrate that Saturn is less able to eject planetesimals from the Solar System than Jupiter. In the SNJ simulations, Saturn boosted a number of particles into longer-period orbits but ejected fewer than in the JNS runs. This manifested as repeated passages through the terrestrial planet region and as a steady, continuous rise in the SNJ curve, as evidenced in all four panels of Fig. 4.

In the case of the SNJ simulations, a small number of particles had many passes through the inner Solar System, for a very high average number of passes per particle, apparent in Table 2. Even though the JNS runs produced a similar total number of terrestrial planet crossings as the full-mass J/S simulations (Fig. 4 and Table 2), the JNS runs kicked far fewer particles into the inner Solar System than the J/S runs (774 vs. 2791) for a higher average number of passes per particle (4384 vs. 2422, JNS vs. J/S runs, respectively). Only 17% of the number of J/S particles were perturbed into Earth-crossing orbits in the JNS runs (209 vs. 1209) for a far higher average number of passes per particle (7742 vs. 826).

Sarafian *et al.* (2014) suggested that Earth's water accumulated not from a late infall of comets, as is widely believed, but rather water accreted early from a source more chondritic in nature. The results of the simulations presented here—particularly those displayed in Fig. 4—suggest that these two scenarios are not mutually exclusive. Grazier *et al.* (2014) showed that even an embryonic J/S pair can deliver significant amounts of volatile-laden planetesimal material to the Asteroid Belt, and Fig. 4 suggests that it can also deliver material to the terrestrial planets in this time frame. To confirm such results properly would require simulations that use a more realistic model of the early Solar System—in particular, the incorporation of gas drag—and is beyond the scope of the current work. In a previous study, Grazier *et al.* (2014) found that the incorporation of gas drag actually increased the delivery of material from the J/S reservoir into the outer Asteroid Belt, and the same would likely be true for the terrestrial planet region.

For objects arriving from the outer Solar System, the lowest impact velocity scenario would occur when the planetesimal and target planet velocity vectors are parallel or along-track, and the particle approaches from the direction antiparallel to the planet's velocity vector: a ''tail chase'' geometry. While most terrestrial impacts would have velocity components in both the along-track and cross-track directions, the geometry that would most likely lead to accretion occurs when the planetesimal's perihelion is the same as the planet's orbital distance, and it approaches in the direction opposite the planet's velocity vector.

The orbit for a tail-chase impact with Earth occurs where the planetesimal aphelion is fixed at Jupiter (5.2 AU); it therefore has a semimajor axis of 3.1 AU, a period of just under 5½ years, and an impact velocity of $\sim 8.9$ km/s. In a related scenario, where the planetesimal's aphelion is fixed at Neptune (30 AU), the orbit has a semimajor axis of 15.6

AU, a period of 61 years, and an impact velocity of $\sim 11.7$ km/s (1.7 times the energy of an object whose aphelion is at Jupiter if the masses are equal). In the case of a tail-chase impact for a comet with an aphelion at 100 AU, the orbit's semimajor axis is 50.5 AU, its period is just under 360 years, and it has an Earth impact velocity of $\sim 12.2$ km/s (1.9 times the energy of an object whose aphelion is at Jupiter if the masses are equal). The odds of accretion in this scenario, therefore, would seem to fall heavily in favor of objects from reservoirs closer to the Sun.

Planetary close approaches can cause one apse of a planetesimal orbit to become fixed at the planet's heliocentric distance. Horner *et al.* (2003) even proposed a classification scheme for outer Solar System objects, based upon which planet controlled the perihelion and which controlled the aphelion. What Fig. 5 reveals is that, although embryonic jovians are capable of delivering significant material to the inner Solar System, a full-mass Jupiter—to a lesser extent Saturn—is not only capable of that but is also able to convert Centaur objects from the outer reservoirs into Jupiter-family comets, irrespective of their zone of origin. If Jupiter fixes the aphelia of terrestrial-planet-crossing planetesimals at its orbit, not only do terrestrial planet crossers have shorter periods and more opportunities to impact terrestrial planets, they also have impact velocities into the terrestrial planets that are largely independent of the planetesimal zone of origin. This increases the likelihood that impacts will lead to accretion rather than atmospheric impact erosion. Jupiter, then, is less of a ''barrier'' and more of a ''gatekeeper'' to the inner Solar System—a gatekeeper that, as noted above, may have served some very important roles in the evolution of life on Earth.

After Jupiter becomes large enough to create many Jupiter-family comets from Centaurs, many of these objects also make frequent and fairly slow passes through the Asteroid Belt (Levison *et al.*, 2009; Grazier *et al.*, 2014), and this transition occurred back when asteroids were more populous. This not only increases the likelihood of collisions and mixing of the two populations, it also increases the likelihood that collisions could alter the orbits of existing asteroids, perturbing them into the inner Solar System as well.

In previous work by Grazier *et al.* (2014), jovian embryos fixed planetesimal aphelia at Jupiter's distance for objects with perihelia in the outer Asteroid Belt; they did not fix the aphelia for planetesimals with perihelia in the terrestrial planet region—likely because they simply are not massive enough. An interesting follow-up study would be to examine more thoroughly the statistics of orbits of planetesimals whose aphelia are fixed by Jupiter, as a function of Jupiter's mass evolution, to determine whether the transition from the type of inner-planet-crossing orbits in the planetary embryo simulations to the full-mass simulations (*e.g.*, Fig. 5) is gradual or abrupt, and whether that transition occurred when there was still appreciable planetesimal material left interior to Neptune. In particular, it would be interesting to determine when that transition occurred relative to the point when the system was able to deliver more material to Earth-crossing orbits from the S/U zone than J/S, as shown in Fig. 4. If the transition was early, what implications does this have for Earth accreting volatile compounds from the outer Solar System and the Asteroid Belt? If early or late, are there implications for the Late Heavy Bombardment? Did the Late Heavy Bombardment ''scan'' progressively deeper through the inner Solar System? As noted, this study ignored the effects of gas drag and other nongravitational forces, which should be included in such a follow-up study.

In the case of our full-mass simulations, kinetic theory calculations suggest that the J/S zone evolves 2 orders of magnitude faster than the other two reservoirs (Grazier 1999a, 1999b). Nevertheless, if the full-mass simulations were extended by a factor of 10, the distribution of the remaining particles at the end of 1 Gy would look very similar to Fig. 2b.

Many more planetesimals survived between the orbits of Jupiter and Neptune in the planetary embryo simulations. Kinetic theory also predicts that the J/S full-mass simulations evolve 2 orders of magnitude faster than the corresponding embryo integrations, so the embryo systems are not fully evolved at the end of 100 My (Grazier *et al.*, 2014). Extending those simulations to 1 Gy would yield a final scenario much different than shown in Fig. 2a.

As shown by the simulations here, which parallel those of previous studies (Levison and Duncan, 1997; Grazier *et al.*, 2007; Morbidelli, 2008), after full-mass and planetary embryo simulations have run their course, many survivors reside in the scattered disk. Of the remainder that survived in all of the 100 My integrations, many were cast out to extreme distances, on highly eccentric orbits, consistent with current models of early Oort cloud formation (Morbidelli, 2008). While bound to the Solar System in a computer simulation, gravitational perturbations from galactic tides and passing stars would render objects beyond $10^5$ AU practical ejectees (Nurmi *et al.*, 2001; Emel'yanenko *et al.*, 2007). Most of the full-mass J/S survivors fell into this ''practical ejectee'' category, as did many of the S/U, U/N, and J/S embryo survivors.

Based upon its orbital elements when Hale-Bopp was first observed, the comet seems to have made its last perihelion passage 4200 years ago in July 2215 BC, when its closest approach to Earth was 1.4 AU. Numerical integrations reveal that the comet likely had a very close approach to Jupiter in June of that year, and 2215 may have been its first inner Solar System apparition (Marsden, 1997). When Hale-Bopp was inbound to the inner Solar System in April 1996, it made a distant pass of Jupiter. Even though the comet's closest point of approach was 0.77 AU, the gravitational perturbation from Jupiter was enough to modify the orbit, reducing its semimajor axes to 370 AU from 525 AU. Its period, therefore, shortened from 4200 years to just over 2500 (Yeomans, 1997). Even more dramatic is the pass by Earth of Comet D/1770L1 Lexell in 1770, which given its closest point of approach of 0.0146 AU from Earth was the closest cometary near-miss in recorded history. Three years prior, that comet had a close approach to Jupiter, which altered its orbit into an Earth-threatening one (Celletti and Perozzi, 2007; Leverington, 2003).

The fact that particles were propelled into longer-period cometary orbits allowed us to examine Jupiter's role as a shield in the colloquial sense promulgated by popular media. Horner and Jones (2008a) noted that ''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.'' While this statement is true, our simulations had over 48,700 instances where objects on cometary orbits, with aphelia beyond the orbit of Neptune, had encounters with Jupiter, and only 5% of those resulted in ejections (and all but two of those involved objects on orbits with aphelia greater than 100 AU). Far more interactions caused planetesimals to be pulled into tighter orbits—with more opportunities to impact Earth—than were either kicked farther out into the Solar System or ejected. Similarly, over half of Saturn encounters resulted in planetesimals acquiring more tightly bound orbits, with lower periods than they had pre-encounter. For all the planetesimal encounters with Jupiter, only seven resulted in impacts; none involved objects with aphelia greater than 100 AU or perihelia that made them Earth-threatening. In short, these simulations illustrate that Jupiter is not a shield in any sense other than it occasionally accretes objects that, one day, might be perturbed into the inner Solar System. A total of 473 objects with aphelia greater than 30 AU collided with Saturn, but that does not make that planet a shield in the colloquial sense any more than Jupiter—none of those objects were Earth-threatening.

By examining the different types of encounters that occurred between long-period planetesimals and both Jupiter and Saturn, we have demonstrated some remarkable complexity with regard to the effects of the jovian planets on the dynamics of early Solar System planetesimals. The values of Table 3 do not fully reflect the intricacy of jovian planet ''shielding'' of the inner Solar System. For our full-mass simulations, we found 2371 instances of particles that had positive energy relative to the Solar System—were on unbound trajectories—and had subsequent close encounters before meeting our ejection criterion. We found 1189 instances where a particle was on a hyperbolic trajectory but underwent a subsequent close approach and became rebound (765 times for inbound particles, 424 outbound). This finding illustrates another way jovian planets can increase the odds of Earth and terrestrial planet impacts, that is, by giving many particles on highly eccentric, even hyperbolic orbits ''second chances.'' Of the many objects from the deep Solar System that had encounters with Jupiter or Saturn, as was the case with Hale-Bopp, over half had their periods reduced, giving them more frequent opportunities to collide with terrestrial planets. Like Comet Lexell, many were Earth-threatening only if a jovian planet made them so.

The degree of complexity on display in these simulations reinforces the conclusions of Horner *et al.* (2010), which were that ''in the future, any planetary systems found to host potentially habitable exo-Earths should be examined individually in great detail to ascertain the various factors that could impact upon their habitability.'' Rather than adopting a blanket assumption about what extrasolar systems do and do not require to have habitable Earth-like planets, like jovian planets to deflect planetesimals either from or into the terrestrial planet region, each system should be examined on a case-by-case basis.

We also have clues that these simulations accurately mirror the type of complexity found in the Solar System. Returning to the apparition of D/1770 Lexell, after threatening Earth in 1770 that comet again had an encounter with Jupiter in 1779 that ejected Lexell from the Solar System. This real-world example demonstrates the nature of Jupiter as both benefactor and menace, as cosmic Jekyll and Hyde.

## 5. Conclusion

With a hyperaccurate integration technique, the simulations presented made it possible to revisit the notion that Jupiter protects Earth from extinction-level impacts. Jupiter and the other jovian planets are capable of delivering material from the outer Solar System to the terrestrial planet region from the time they were planetary embryos. The simulations also show that although Jupiter helps clear the outer Solar System of unaccreted planetesimals, rather than being an effective shield, it teams with Saturn to kick a significant fraction of objects—initially nonthreatening—into the inner Solar System.

As a young Jupiter's size increased, not only did it kick a larger number of planetesimals into the scattered disk and Oort cloud—even ejecting them entirely—it also modified the orbits of many planetesimals into orbits having aphelia near Jupiter, with shorter periods and higher inner-system passage frequencies. In those instances, terrestrial planet impact velocities may have been relatively low and independent of original source zone. Still, although Jupiter dominates the dynamics of the outer Solar System, it does so mostly in concert with the other jovian planets, primarily Saturn. These simulation results strongly suggest that a system with a jovian planet—or multiple jovian planets—exterior to the terrestrial planet region is, in fact, beneficial for the development of life.

The colloquial view of jovian planet shielding propagated by the media, that Jupiter or Saturn gobble up comets having Earth in their crosshairs, is simply not borne out by these simulations. Wetherill's 1994 paper began with a laudable goal, and it is a worthwhile read to appreciate the deep questions that study attempted to address. As we have done, Wetherill performed computational simulations to address those questions, using approximation techniques necessary to get maximum benefit of the computation available at the time. Since the publication of that paper, astronomers have discovered that jovian planets are ubiquitous. With the benefit of over 12 Moore's law (Moore, 1965) doublings in between, we have simulated some of the same scenarios as in Wetherill's paper with a far more accurate model and found that few of its conclusions stand the test of time. Perhaps the most important lesson of Wetherill's 1994 paper might be a cautionary one. It serves as an excellent example of how unchallenged notions can become firmly entrenched in scientific thinking (and, in fact, in the popular zeitgeist) and then propagated dogmatically.

If the relationship between impact events and life on Earth is aptly described as ''It's complicated,'' the role Jupiter plays in this scenario complicates matters further. Clearly, Jupiter alone is not an efficient defender of the inner Solar System from comets originating in the outer Solar System; as these simulations showed, it likely shunts as many comets toward the terrestrial planets as it deflects away. Yet, as demonstrated here, Jupiter—at different key points in history—would have been instrumental in both helping create the conditions for life on Earth and also inciting mass extinctions.

If a gust on a windy day kicks up a cloud of dust and hurls it against a screen, some dust grains will pass through unimpeded, some will glance off the mesh and pass through anyway, and a small fraction of dust grains will impact the mesh and be repelled. Rather than ''Jupiter as impenetrable screen,'' a better metaphor for the planet's role is ''Jupiter as screen door.''

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**Abbreviations Used**

JNS = Jupiter no Saturn
J/S = Jupiter/Saturn
SNJ = Saturn no Jupiter
S/U = Saturn/Uranus
U/N = Uranus/Neptune