Eight billion asteroids in the Oort cloud

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ABSTRACT

The Oort cloud is usually thought of as a collection of icy comets inhabiting the outer reaches of the Solar system, but this picture is incomplete. We use simulations of the formation of the Oort cloud to show that ∼4 per cent of the small bodies in the Oort cloud should have formed within 2.5 au of the Sun, and hence be ice-free rock-iron bodies. If we assume that these Oort cloud asteroids have the same size distribution as their cometary counterparts, the Large Synoptic Survey Telescope should find roughly a dozen Oort cloud asteroids during 10 years of operations. Measurement of the asteroid fraction within the Oort cloud can serve as an excellent test of the Solar system's formation and dynamical history. Oort cloud asteroids could be of particular concern as impact hazards as their high mass density, high impact velocity, and low visibility make them both hard to detect and hard to divert or destroy. However, they should be a rare class of object, and we estimate globally catastrophic collisions should only occur about once per billion years.

Key words: comets: general – minor planets, asteroids: general – Oort cloud.

1 INTRODUCTION

The Sun is surrounded by a cloud of hundreds of billions of comets, with semimajor axes of 10^4–10^5 au. They did not form at such distances, but rather within a few tens of au of the Sun, and were scattered on to large (10^4 au $\lesssim a \lesssim 10^5$ au), highly eccentric ($e \sim 1$) orbits by the planets (Oort 1950; Duncan et al. 2008). At distances of thousands of au or more from the Sun, perturbations from the Galactic tide and nearby stars raised the perihelia of these comets to beyond the reach of Neptune, allowing their orbits to be stable for billions of years (Heisler & Tremaine 1986; Duncan, Quinn & Tremaine 1987; Dones et al. 2004).

As the Solar system is a complex dynamical system of eight planets and numerous small bodies and satellites, and as it is perturbed by passing stars (Oort 1950), giant molecular clouds (Biermann 1978), and the Galactic tide (Heisler & Tremaine 1986), all of which may be important for the evolution of Oort cloud comet orbits, the problem of the formation of the Oort cloud is typically approached with *N*-body simulations. It is generally believed that the planets have migrated during the Solar system's history (e.g. Fernandez & Ip 1984; Malhotra 1993; Tsiganis et al. 2005; Walsh et al. 2011), although the details of these scenarios are uncertain. Likewise, the birth environment of the Sun (Adams 2010) and its subsequent migration through the Galaxy (Sellwood & Binney 2002; Roškar et al. 2008) are unknown. The properties of the Oort cloud can be used to constrain the dynamical history of the Solar system's planets (e.g. Brasser & Morbidelli 2013; Lewis, Quinn & Kaib 2013; Fouchard et al. 2014) and the Solar neighbourhood over its history (e.g. Levison et al. 2010; Kaib, Roškar & Quinn 2011; Brasser et al. 2012), but different combinations of the models of the dynamical history of the Solar system, the history of external perturbers, and the initial populations of small bodies can produce the same total population of Oort cloud comets.

To break this degeneracy, one approach is to try to associate Oort cloud objects with their birth region. A similar approach has already been suggested for main belt asteroids (DeMeo & Carry 2014). Traditionally, small bodies have been divided between comets (icy bodies on highly eccentric orbits), and asteroids (rock-iron bodies on lower eccentricity orbits). However, while these properties were well correlated observationally, the outgassing of cometary nuclei increases their brightness by orders of magnitude, making them much easier to discover; meanwhile, objects in the asteroid belt had gigayears to outgas their surface volatiles, more than enough time to reduce or eliminate any activity (Weissman 1980; Levison & Duncan 1997; Schorghofer 2008). Questioning this assumption is motivated by the discovery that the separation between asteroids and comets is not a clean one, with icy, outgassing bodies found in the main asteroid belt (called active asteroids or main-belt comets; Hsieh & Jewitt 2006; Haghighipour 2009; Jewitt, Li & Agarwal 2013), and the overlap between the orbital distributions of comets and asteroids (Tancredi 2014). Similarly, modelling the dynamics of small bodies from the inner reaches of the Solar system has found that they are commonly ejected (Jackson & Wyatt 2012), so we

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should also expect near-ejections to produce rocky, ice-free bodies in the Oort cloud, which we will refer to as Oort cloud asteroids. This possibility was considered by Weissman & Levison (1997) to explain the appearance of 1996 PW, an object in a long-period comet (LPC) orbit which did not display outgassing. They inferred that ∼1 per cent of the Oort cloud should be from the region of 3.3 to 5.2 au, based on the simulations of Duncan et al. (1987). Those simulations assumed that bound objects with aphelion $Q > 10^4$ au became comets, rather than modelling the effects of the Galactic tide and passing stars. Scaling the 3.3–5.2 au result down to 1 au, Weissman & Levison (1997) estimated 2.3 per cent of the Oort cloud to have come from the region interior to Jupiter's orbit. Follow-up observations found that although 1996 PW's appearance was compatible with an S- or D-type asteroid, it was also compatible with an extinct comet (Davies et al. 1998; Hicks et al. 2000), and the issue of rocky bodies in the Oort cloud appears to have been subsequently neglected.

Modelling of the evolution of protoplanetary discs suggests the snow line may have been as close to the Sun as 0.7 au and as far as 10 au (Garaud & Lin 2007; Min et al. 2011; Martin & Livio 2012) during its evolution. However, observations of the population of active asteroids (sometimes called main belt comets) suggest that the snow line separation objects that formed with water ice and those that formed without it in the Solar system is at 2.5 ∼ 3.0 au (Bertini 2011; Sonnett et al. 2011). Given this, Oort cloud asteroids from the region interior to 2.5 au could represent a significant fraction of bodies in the present-day Oort cloud.

To address the question of how common asteroids should be in the Oort cloud, we perform simulations of the Oort cloud's formation, considering small bodies starting with dynamically cold orbits with semimajor axes from 0.5 to 50 au. In Section 2, we describe our numerical setup. In Section 3, we present the results of those simulations. We estimate the detectability of such bodies in Section 4, their impact rate on the Earth in Section 5, and finish up with some discussion in Section 6.

2 MODEL

We perform simulations with the Mercury suite of *N*-body integrators (Chambers 1999), augmented with the Galactic tidal model of Veras & Evans (2013) and the stellar flyby model of Veras, Shannon & Gaensicke (2014). Interior to 6 au, simulations are performed with the outer seven planets (i.e. excluding Mercury), beginning with their present-day[1] positions and velocities, with the ecliptic rotated to be inclined 67deg to the Galactic disc. Integrations are performed with an eight-day timestep. For test particles at 6 au and beyond, we include only the outermost four planets, which allows us to use a 120 d timestep and somewhat lessen the computational burden. Simulations are run for 4.5 Gyr, or until all test particles have been removed. Particles are removed by collisions with a planet or the Sun, or when they are more than 250 000 au from the Sun, exceeding the maximum extent of the Hill ellipsoid around the Sun (Veras & Evans 2013).

We use at least 1000 particles per au, except between 2.0 and 5.5 au, where the long-term stability of the asteroid belt and Jupiter Trojans make this choice unfeasible, and beyond 30 au, where long-term stability again makes this unfeasible. There we use at least 100 particles per au. Bin widths are 0.1 au from 0.5 to 6.0 au, and 1.0 au thereafter. Initial eccentricities are chosen randomly and uniformly

from 0.00 to 0.05, and inclinations are chosen randomly and uniformly from 0 to $0.05\frac{\pi}{2}$, and the other orbital angles randomly and uniformly from 0 to 2π.

3 RESULTS

We plot the fate of particles after 4.5 Gyr of evolution in Fig. 1. Beyond 1.5 au, ejection is the most common outcome for particles which are lost. Interior to 1.5 au, no single outcome dominates, with ejection, and collisions with Earth, Venus, and the Sun all important. The majority of particles between 2.2 and 3.5 au (i.e. the asteroid belt), and beyond 43 au (i.e. the main Kuiper belt) are retained. Significant numbers of Jupiter Trojans, Neptune Trojans, and inner Kuiper belt objects (Holman & Wisdom 1993; Duncan, Levison & Budd 1995) are also retained. We separate particles which are Oort cloud comets at 4.5×10^9 years from other surviving particles; we define particles to be members of the Oort cloud if they lie on an orbit with perihelion $q \geq 40$ au and semimajor axis $a \geq 1000$ au; the former criterion selects those objects that are not interacting with the planets by close encounters; the latter criterion excludes Kuiper belt-type objects that begin with $q \geq 40$ au but have aphelia too small to interact with the Galactic tide or passing stars.

Only about 25 per cent of our Oort cloud objects are retained until 4.5 Gyr,[2] so to obtain a bigger sample we focus on objects that are ever Oort cloud objects. The fraction of objects that are ever Oort cloud objects is plotted in Fig. 2 (left-hand panel). Interior to Jupiter's orbit, slightly less than 1 per cent of objects ever become Oort cloud objects, rising to ∼10 per cent for objects beginning beyond the orbit of Uranus. Qualitatively, this outcome is unsurprising, since Fernandez & Ip (1981) found that Neptune and Uranus produce Oort cloud objects much more effectively than do Jupiter or Saturn, and Lewis et al. (2013) found this to be generally true of Neptune-mass planets versus Jupiter-mass planets.

To transform the odds of a single small body ever becoming a member of the Oort cloud to the fraction of the Oort cloud, we need to know the initial populations at all distances from the Sun. The scaling usually assumed is that the surface density of the proto-Solar nebula followed $\Sigma \propto r^{-1.5}$, based on the mass distribution of planets today (Weidenschilling 1977; Hayashi 1981). Called the Minimum Mass Solar Nebula (MMSN), this construct assumes all the solid mass of the nebula ended up in planets. To produce an initial surface density of small bodies to calculate the composition of the Oort cloud today, we assume the same scaling can be applied to the small bodies, and that all small bodies have the same size distribution. Observations of LPC today suggest the total mass of the Oort cloud is $1 \sim 10 M_\oplus$ (Weissman 1996; Francis 2005). As not all Oort cloud comets have survived to the present day, this suggests the primordial mass of the solids in the Oort cloud was comparable to the total mass of solids in planets used to derive the MMSN. Thus although this assumption is well-motivated,[3] how well it is likely to represent the correct initial conditions is not entirely clear. Thusly caveated, we plot the total number of bodies that we infer ever make it into the Oort cloud in Fig. 2 (right-hand panel).

We simulated particles out to 50 au, but the Solar nebula should have had a significant density drop-off at 30 au (Gomes, Morbidelli

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[1] Midnight of 1998 July 6.

[2] Similar results are found by other groups (e.g. Mazeeva 2004; Leto et al. 2008; Fouchard et al. 2011).

[3] Some planet formation models expect a switch in the character of the growth when the mass of planets equals the mass of planetesimals, (see Goldreich, Lithwick & Sari 2004).
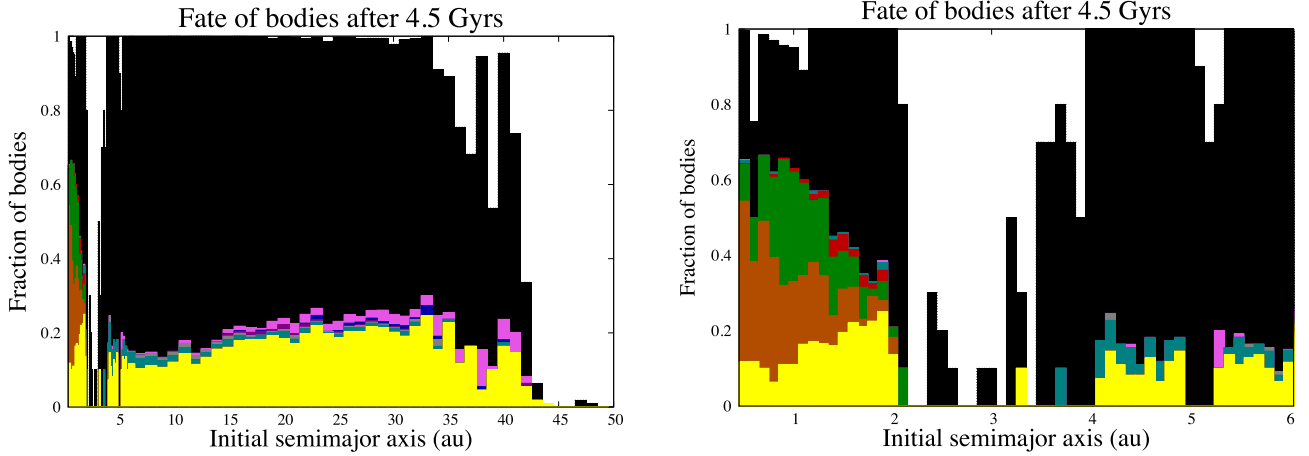
Figure 1. The status of the test particles at 4.5 Gyr. The left-hand panel shows the entire Solar system, while the right-hand panels zooms in on the inner 6 au. From bottom to top, the outcomes are impacted the Sun (yellow), impacted Venus (brown), impacted Earth (green), impacted Mars (red), impacted Jupiter (turquoise), impacted Saturn (grey), impacted Uranus (purple), impacted Neptune (blue), Oort cloud comet (pink), ejected (black), and otherwise still active (white).
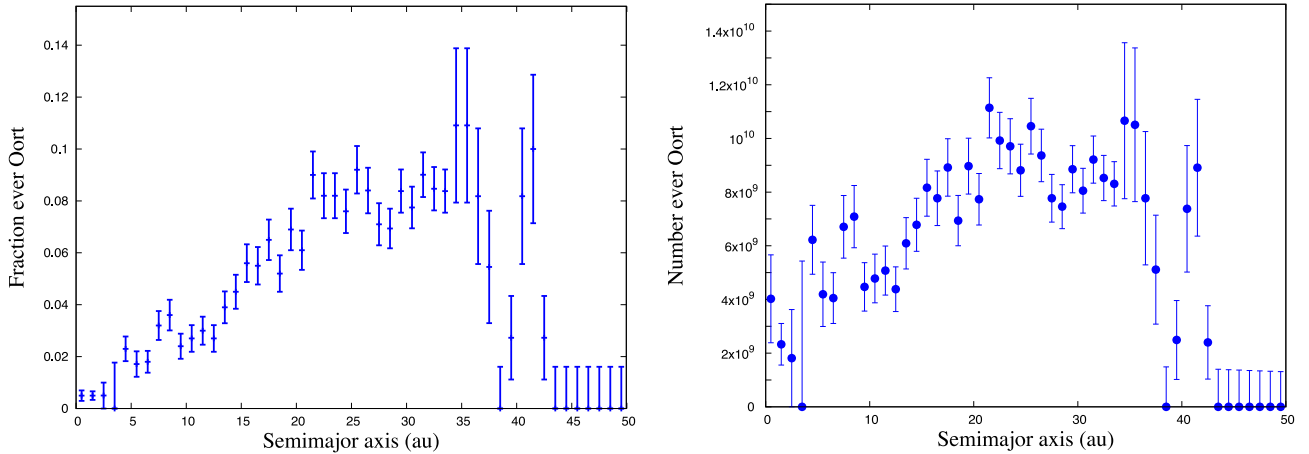

Figure 2. In the left-hand panel, we plot the fraction of all objects that were ever Oort cloud objects before 4.5 Gyr. Only ∼25 per cent remain Oort cloud objects after 4.5 Gyr of evolution. In the right-hand panel, we plot the total number of objects put into the Oort cloud, by assuming that the surface density of the objects begins with the same scaling as the MMSN, normalized so the total number of particles is 2×10^{11} to be congruent with observations.

& Levison 2004). Approximating this as a sharp cut-off, we find that rocky bodies from within 2.5 au of the Sun should be ∼4 per cent of the total population of the Oort cloud.

To better understand the fate of the particles that survive the simulations, we plot the dynamical lifetime of small bodies across the Solar system in Fig. 3. Here we see that the asteroid and Kuiper belts are the only places in the Solar system where small bodies are reliably stable for 4.5 Gyr. The simulations have some particles as Trojans of all the planets except Mars; in the Solar system stable Trojans are only known for Jupiter (Wolf 1907), Neptune (Brasser et al. 2004), and Mars (Scholl, Marzari & Tricarico 2005), but shorter lifetime Trojans are also known for Venus (de la Fuente Marcos & de la Fuente Marcos 2014), the Earth (Connors, Wiegert & Veillet 2011), and Uranus (Alexandersen et al. 2013). A couple of Trojans of Uranus and Saturn surviving is not unexpected (Nesvorný & Dones 2002), and we find 3 and 2, respectively. Some surviving objects become scattered disc objects/centaurs. A significant number of objects remain in the inner Solar system between the terrestrial planets, a result previously found by Evans & Tabachnik

(1999, 2002). These are not observed, whatever physics caused their loss is not included in our simulations, and their absence remains an open problem. The simulations also show a slowly decaying population between Uranus and Neptune (Holman 1997), though with only a few thousand particles, the last member is lost at 3.3×10^9 years.

4 DETECTABILITY WITH LSST

To test this prediction, we want to find some asteroids inbound from the Oort cloud. The number of Oort cloud comets with individual masses of ∼1.7×10^{17} g or greater is estimated from observations to be ∼2×10^{11} (Francis 2005). The number of comets drops off strongly at lower masses, with only ∼5×10^{11} Oort cloud comets with masses above ∼10^{12} g (Francis 2005), although the typical size and size at which the drop off occurs is somewhat uncertain (Weissman 1996; Snodgrass et al. 2011; Fernández & Sosa 2012). Given this, when considering surveys for Oort cloud asteroids, we can approximate all comets as having the same mass, in which case the total mass of Oort cloud comets is $M_c \sim 4 \times 10^{28}$ g, We
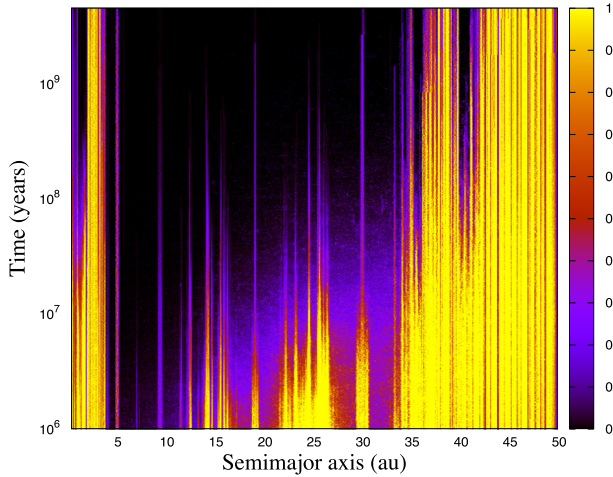
Figure 3. Fraction of particles at a given semimajor axis, plotted against time. The Asteroid and Kuiper belts show up strongly, as most particles are stable; the Jupiter and Neptune Trojans are also visible, as well as the stable regions of the inner Solar system (Evans & Tabachnik 1999). Two Saturnian Trojans and three Uranian Trojans also persist. The concurrence between this and the observed population of small bodies is pretty good, although our non-migratory Neptune fails to capture Plutinos and other resonant objects, and the question of what eliminates the inner Solar system bodies remains open.

found the total mass of Oort cloud asteroids to be 4 per cent that of comets, or $M_r \sim 2 \times 10^{27}$ g. Since most Oort cloud asteroids come from the terrestrial planet region, where the primordial mass distribution is uncertain, we assume a single-mass distribution for them, by default the same as comets ($m_r \sim 1.7 \times 10^{17}$ g). For a reasonable density for rock (2.5 g cm^{-3}), this gives Oort cloud asteroids with radii $r_r = 2.3$ km. The number of Oort cloud asteroids is then $n_r = M_r/m_r \sim 8 \times 10^9$ rocky bodies bigger than 2.3 km in the Oort cloud – *the Oort cloud has more asteroids than the Asteroid belt does!*

The Large Synoptic Survey Telescope (LSST) is expected to detect objects to an apparent magnitude limit of $m \sim 24.5$ (Moro-Martín, Turner & Loeb 2009). Oort cloud asteroids with radii 2.3 km and albedo $\alpha = 0.16$, typical of inner main belt asteroids (Strom et al. 2014), would be detectable to a distance of $b \sim 13$ au; for other sizes and albedoes $b \propto \alpha^{0.25} r_r^{0.5}$. Given an isotropic velocity distribution, Oort cloud comets are expected to have a linearly uniform distribution of perihelia [or $n(q < q_0) \approx q_0/a$] (Dones et al. 2004). For the typical $a = 3 \times 10^4$ au orbit, the number of Oort cloud asteroids ever detectable is thus $n_d \sim n_r b/a \sim 3.5 \times 10^6$.

Over LSST's 10 year mission (Moro-Martín et al. 2009), only a small fraction of Oort cloud asteroids will be at or near perihelion. Assuming Oort cloud asteroids travel on orbits with $a \approx \infty$ and $e \approx 1$, they spend

$$\tau = \frac{4}{3} b^{1.5} \left(2GM_\odot \right)^{-1/2} \tag{1}$$

within a distance b of the Sun. Setting $b = 13$ au yields an inner Solar system passage time, during which the bodies are detectable by LSST, of $\tau \sim 7$ yr. For the typical $a = 3 \times 10^4$ au orbit, the orbital period is $P \sim 5 \times 10^6$ yr, and a typical Oort cloud asteroid spends $\tau/P \sim 10^{-6}$ of its time being detectable. At any given time, we should expect $n_d \tau/P \sim 5$ such objects to be detectable, a number that scales as $r_r^{-7/4}$. Additionally, with LSST expected to survey for ~10 years, new objects should enter the sphere of detection at a rate of $n_d/P \sim 0.7$ yr^{-1}, for a total of 7 additional objects, a number

that scales as $r_r^{-5/2}$. In total we expect ~12 such objects should be detectable, a number that drops to less than one if $r_r > 14$ km, but will be much larger if r_r is smaller than 2 km.

5 EARTH IMPACT RATE

Earth-crossing LPC nuclei pose a particular problem for impact mitigation. Whereas surveys of Near Earth Asteroids (NEAs) can enable us to identify potentially hazardous objects years or decades in advance of a possible impact, LPC nuclei are not typically discovered until they become active. As a result most LPC nuclei are not discovered until they have crossed the orbit of Jupiter and many are not seen until they are rather closer to the Sun (e.g. Marsden & Steel 1994). An LPC nucleus on a parabolic orbit with perihelion at less than 1 au will take less than a year to cross the distance between the orbits of Jupiter and Earth, and discovery only a few months before perihelion is common (Marsden & Steel 1994). A nuclear detonation is probably the only plausible mitigation method that could achieve a sufficient orbital change with such a short lead time, and even then it would probably only be possible if a pre-existing delivery vehicle could be used (Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies Space Studies Board; National Research Council 2010).

An asteroid inbound from the Oort cloud presents an even more severe warning time problem than an icy LPC nucleus, since it will (presumably) never become active and would remain as a dark rock until it appears in our skies. We might thus never know what hit us. As such it behoves us to estimate the probability of a catastrophic Oort cloud asteroid impact occurring.

LPC nuclei with perihelion $q < 1$ au have an $f_c \sim 2.2 \times 10^{-9}$ chance of impacting the Earth per orbit (Weissman 2007). For the population of Oort cloud asteroids discussed in Section 4, this corresponds to an impact once every $f_c P/n$ ($q < 1$au) ≈ 8 Gyr. However, the smaller bodies we neglected there as too dim to be important for detection in surveys can be important as impactors. For NEAs the threshold radius at which an impactor will have globally catastrophic consequences has been estimated to be 500 m. A 500 m object with a typical density of 2500 kg m^{-3} impacting at a typical velocity of 20.9 km s^{-1} (Stuart & Binzel 2004) has an impact energy of 3×10^{20} J. By comparison typical LPC nuclei impact velocities are almost three times higher at around 55 km s^{-1} (Marsden & Steel 1994; Weissman 2007), and thus a Oort cloud asteroid of the same size (and density) will have almost an order of magnitude higher impact energy, such that the equivalent threshold size for an Oort cloud asteroid is around 250 m. Estimates of the impact frequency for NEAs larger than 500 m vary between once every 0.1 Myr (Hughes 2003) and once every 0.6 Myr (Stuart & Binzel 2004).

Estimates of the rate of LPC nuclei impacts are somewhat more difficult to determine. Since 1700, six comets per century have passed within around 0.1 au of Earth (e.g. Sekanina & Yeomans 1984, see also www.minorplanetcenter.net/iau/lists/ClosestComets.html), implying an impact rate of about once every 40 Myr (a similar rate was estimated by Weissman 2007). This is in agreement with the impact probabilities per perihelion passage calculated by Marsden & Steel (1994, again see Weissman 2007), for a total of 11 Earth-crossing comets per year. 11 Earth-crossing comets per year is also the frequency implied by 6 close encounters per century, which is in agreement with the bias corrections of Everhart (1967) and the dynamical arguments of Weissman (2007), and indicates that the current discovery rate of around 3

per year (Fernández & Sosa 2012) is still rather incomplete. If we use the conversion between absolute H magnitude and size of Sosa & Fernández (2011) around half of the comets used by Sekanina & Yeomans (1984) have nuclei larger than 250 m in radius, and at smaller size the slopes of the size distributions of NEAs and Earth-crossing cometary nuclei are fairly similar. We thus estimate that an impact with an Oort cloud asteroid larger than 250 m in radius would likely be a once-in-a-Gyr event. The relative contribution of Oort cloud asteroid impacts at different impact energies depends on their size distribution, and how it differs from that of comets or NEAs. Integrated over all sizes comets account for a few per cent of Earth impactors by impact energies, so we expect Oort cloud asteroids to account for $\sim 10^{-3}$ of the total impactor population. Tunguska-like impacts, capable of smiting a city, occur every 10^3 years (Brown et al. 2002), and thus we expect Tunguska-sized Oort cloud asteroid impacts should occur every $\sim 10^6$ years. The inferred upturn in number of impactors between ~ 250 and ~ 25 m is consistent with a collisionally evolved population (Dohnanyi 1969; O'Brien & Greenberg 2003), which is expected for such small Oort-cloud objects (Stern & Weissman 2001).

6 DISCUSSION

We simulate the scattering of small bodies in the Solar system, augmented with the effects of the Galactic tide and passing stars, in order to understand the fraction of Oort cloud objects that should come from the inner reaches of our planetary system. We find that for reasonable assumptions, ~ 4 per cent of Oort cloud objects should have come from within 2.5 au of the Sun, and hence be ice-free. Until now, such ice-free objects have gone unnoticed, as they are much dimmer than their icy, active counterparts. LSST, however, should be expected to find roughly a dozen of these objects.

A steeper MMSN, as is sometimes argued for (e.g. Desch 2007; Chiang & Laughlin 2013) would imply that the Oort cloud should contain a higher fraction of asteroids. Similarly, particular dynamical histories of the Solar system, such as the Nice model (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005), Grand Tack (Walsh et al. 2011), or other dynamical clearings of the asteroid belt region (Petit et al. 2002) should predict different fractions of asteroids. Additional physics should continue to remove smaller asteroids from the asteroid belt, such as the Yarkovsky effect, and orbit changes due to collisions, and they may become members of the Oort cloud. Different histories of the Sun's local environment (e.g. Gaidos 1995; Fernández 1997; Kaib et al. 2011) should also make different predictions. Alternate paths for Oort cloud formation would also make different predictions (Levison et al. 2010). This list is not exhaustive, and this constraint would need to be combined with others to discriminate between such models. What we present here should be considered the baseline model for comparison.

No Oort cloud asteroids have definitively been found. However, a few possible candidates exist: Weissman & Levison (1997) postulated an inner Solar system origin for 1996 PW, but the appearance is equally compatible with it being either a D-type asteroid or an extinct comet (Davies et al. 1998; Hicks et al. 2000). Kiss et al. (2013) found that 2012 DR$_{30}$ is best fit as an A-type or V-type asteroid; both represent rocky inner-Solar system material that has been differentiated. However, due to a likely dynamical origin in the Oort cloud they dismissed the possibility that 2012 DR$_{30}$ is a rocky body formed in the inner Solar system. Other Oort cloud asteroids may be hiding among the Damacloids (Jewitt 2005), which have short-period comet orbits but show no outgassing. This example highlights a problem common to all the more tightly bound candi-

dates: distinguishing an object recently escaped from the asteroid belt from an object recently arrived from the Oort cloud but perturbed on to a tighter orbit is difficult (see e.g. Weissman & Levison 1997; Wang et al. 2012). Definitive identification is likely to lie with detecting objects during their first return to the inner Solar system since their near ejection gigayears ago.

Other sources of Oort cloud asteroids should exist – models find ejecta from the Moon-forming impact to have been of the order of a lunar mass (Canup 2004); Mercury's large core and small mantle may be signatures of an impact that ejected of the order of a Hermian mass (Benz et al. 2007); the Martian hemispheric dichotomy may be an impact basin (Andrews-Hanna, Zuber & Banerdt 2008), events that would produce a large number of small bodies. The total amount of ejecta produced by giant impacts during the formation of a terrestrial planet is estimated to be ~ 15 per cent of the final mass (Leinhardt & Stewart 2012), and thus we should expect to find a significant number of such bodies in the Oort cloud. Collision ejecta should begin on higher eccentricity orbits, but the effect is not too significant; comparing our results from 0.9 to 1.1 au to the simulations of moon-forming impact ejecta by Jackson & Wyatt (2012), re-run with eccentric planets, they find the fate of lost particles at 34 per cent ejection, 29 per cent impact the Earth, 26 per cent impact Venus, 9 per cent impact the Sun, and <1 per cent everything else, while we find 33 per cent ejection, 34 per cent impact the Earth, 21 per cent impact Venus, 11 per cent impact the Sun, and <1 per cent everything else.

The rarity of Oort cloud asteroids means that Earth impacts of asteroids from the Oort cloud are quite unlikely to be a threat on human time-scales. From our rate estimates, we find they should produce globally catastrophic collisions around once per gigayear, and locally destructive impacts every million years. Thus although evidence of such occurrences may be found in the geologic record, they are not a pressing concern for the immediate future.

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