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ORIGIN AND EVOLUTION OF THE UNUSUAL OBJECT 1996 PW: ASTEROIDS FROM THE OORT CLOUD?

Paul R. Weissman[1]
Earth and Space Sciences Division, Jet Propulsion Laboratory, Pasadena, CA 91109; pweissman@issac.jpl.nasa.gov
and
Harold F. Levison
Space Sciences Department, Southwest Research Institute, Boulder, CO 80302; hal@gort.boulder.swri.edu
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ABSTRACT

The unusual object 1996 PW was discovered on 1996 August 9 by the Near-Earth Asteroid Tracking automated search camera operating from Haleakala in Hawaii. Although asteroidal in appearance, it was soon determined that the object is in a near-parabolic orbit similar to that of a long-period comet. No object that was not an active comet has ever been discovered on such an eccentric orbit. The discovery of 1996 PW prompted us to examine and evaluate its possible origins, including the intriguing possibility that it is an asteroid from the Oort cloud. Current models for the formation of the Oort cloud argue that most of the material there should be from the Uranus-Neptune region and thus cometary, not asteroidal, in composition. We better quantify these models and show that ∼1% of the Oort cloud population should be asteroids. We find that 1996 PW has almost certainly been a resident of the Oort cloud. However, we find it equally likely that 1996 PW is an extinct comet or an asteroid. Although not conclusive, our results represent a significant change in our understanding of the Oort cloud, because they suggest that the ejection process sampled (1) material from as close to the Sun as the asteroid belt in the primordial solar nebula and hence (2) much warmer formation temperatures than previously thought. This diverse sample is preserved in the Oort cloud.

Subject headings: celestial mechanics, stellar dynamics — comets: general — minor planets, asteroids — solar system: formation

1. INTRODUCTION

The unusual object 1996 PW was discovered on 1996 August 9 by the Near-Earth Asteroid Tracking (NEAT) automated search camera operating from the Air Force Ground-based Electro-Optical Deep Space Surveillance (GEODSS) Observatory on Haleakala in Hawaii (Helin, Pravdo, & Lawrence 1996; Helin et al. 1997). Although asteroidal in appearance, Williams (1996a, 1996b) determined that the object was in a near-parabolic orbit similar to that of a long-period comet. Continued observations of 1996 PW have allowed the determination of the following orbital elements: semimajor axis, $a = 327$ AU; eccentricity, $e = 0.992$; perihelion, $q = 2.54$ AU; inclination, $i = 29\overset{\circ}{.}8$; and period, $p \simeq 5900$ yr (Williams 1996c).

The only objects discovered in such eccentric orbits to date are active long-period comets. However, physical observations have failed to detect any evidence for cometary activity in 1996 PW (Williams, Cartwright, & Fitzsimmons 1996; Mottola & Carsenty 1996; Rabinowitz 1996a, 1996b; Jewitt 1996). The object is described as red in color, similar to S and D asteroids and cometary nuclei. Assuming a typical cometary albedo of 0.04, 1996 PW is ∼15 km in diameter; for a stony asteroid albedo of 0.15, its diameter is ∼8 km.

The question thus arises, What is this unusual object and where did it come from? There are several possibilities. First, 1996 PW could be a long-period comet that has evolved physically to a dormant or extinct state, with its icy surface covered by a lag deposit of nonvolatile dust grains and organics and/or radiation processed so as to sputter away all volatiles. Second, the object could be an asteroid that was ejected to the Oort cloud (Oort 1950; for a review, see Weissman 1996). As such, it most likely experienced the same dynamical evolution as the long-period comets, probably ejected early in the solar system's history and recently thrown back into the planetary system by stellar and galactic perturbations. Third, 1996 PW could be an ecliptic comet (i.e., a comet originally from the region beyond Neptune) that has evolved to a dormant or extinct state and is now evolving outward because of planetary perturbations. Fourth, 1996 PW could be an asteroid that has recently been perturbed out of a stable orbit by the planets and is evolving outward.

[1] Jet Propulsion Laboratory, Mail Stop 183-601, 4800 Oak Grove Drive, Pasadena, CA 91109.

2. DYNAMICAL TESTS

We performed a series of dynamical simulations and calculations to test each of these hypotheses. First, we calculated the probability that 1996 PW is an extinct long-period comet. We assumed that 1996 PW had come from the Oort cloud and followed its evolution inward using a Monte Carlo simulation (Weissman 1979). The dynamical simulation assumed that comets random walk in orbital energy because of planetary perturbations, with the rms magnitude of the perturbation determined by the object's perihelion distance and inclination. The simulation assumed that objects are lost by ejection to interstellar space or by being returned to the Oort cloud ($a > 10^4$ AU). No physical loss mechanisms were included. The initial semimajor axes of objects was set at 2.5×10^4 AU.

Results for 10^7 hypothetical objects with origin in the Oort cloud and the perihelion distance and inclination of 1996 PW are shown in Figure 1, which gives the probable dynamical age of 1996 PW versus the number of perihelion passages. The distribution is sharply peaked, with a maximum value of only six returns and a long tail. The median number of returns is 28, and 95% of the objects with semimajor axes similar to 1996 PW ($a = 200$–500 AU) have ages of 391 returns or less; 99% have made less than 774 returns.

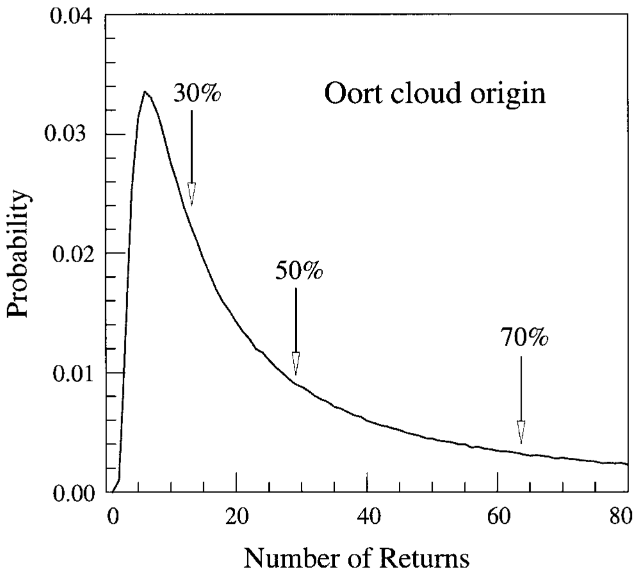

FIG. 1.—Probable dynamical age of an object evolving inward from the Oort cloud to the current orbit of 1996 PW, measured in the number of perihelion returns by the object, as determined by a Monte Carlo simulation. The distribution of dynamical ages in the figure is sharply peaked, with a maximum value at only six returns and a long tail. The median number of returns is 28, and 95% of the comets with semimajor axes similar to 1996 PW have ages of 391 returns or less; 99% have made less than 774 returns. Vertical arrows indicate the cumulative probability.

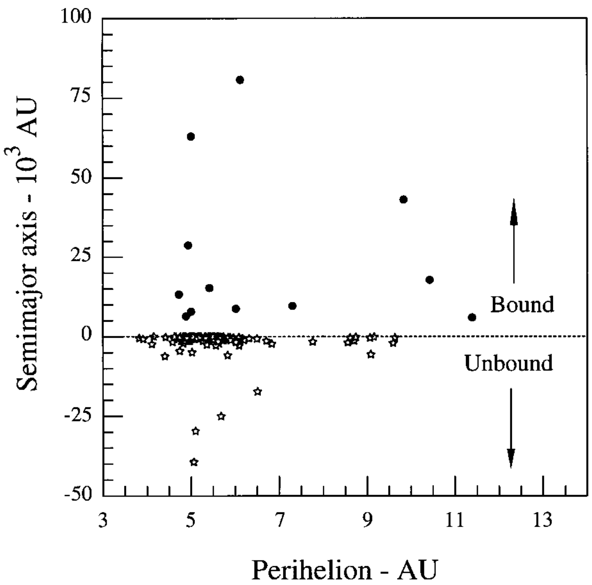

FIG. 2.—The fate of 150 test particles with semimajor axes initially between 3.3 and 5.2 AU, as determined by Levison & Duncan (1997b). Shown in the figure are the semimajor axes, a, and perihelion distances, q, of objects when they were lost from the simulation. Objects with $a < 0$ were ejected from the system and are shown by a star in the figure. Objects with $a > 0$, which are still bound to the solar system and are in the Oort cloud, are shown as circles. The simulation found that ~8% of all objects were placed in the Oort cloud.

How long, then, does it take a comet to evolve physically to a dormant or extinct state? Since cometary volatiles only sublime when the nuclei are close to the Sun, the age of comets is best measured in terms of the number of perihelion passages or returns. Estimates of the physical lifetimes of comets as active bodies vary considerably. As a minimum, one can consider periodic comets Encke and Halley, which both have much smaller perihelion distances than 1996 PW and which have been observed on 56 and 30 returns, respectively (Marsden & Williams 1996). Estimates of the age of comet Halley based on studies of the associated meteoroid streams range from 2.3×10^4 to over 2×10^5 yr, which translates to 300–2600 returns at its current orbital period (Jones, McIntosh, & Hawkes 1989; Weissman 1987). The sublimation lifetime for a 1 km radius, low-albedo water ice sphere with a perihelion distance similar to that of 1996 PW is more than 5000 returns (Weissman 1980). Dynamical studies of the evolution of Jupiter-family comets from the Kuiper belt suggest a median physical age of 12,000 yr as active comets, or ~1600 returns (Levison & Duncan 1997a). Based on these estimates, we assume a conservative physical lifetime for comets of half this latter value, or 800 returns (see § 3 for additional discussion).

This physical lifetime may appear long to those familiar with cometary studies. However, we believe that it is well supported by the references cited, as well as by studies of several periodic comets, using ancient astronomical records to determine the orbits of these comets over the past 2 millennia (Stephenson, Yau, & Hunger 1985; Yau, Yeomans, & Weissman 1994; Yeomans, Yau, & Weissman 1996). These researchers showed that comets Halley, Swift-Tuttle, and Tempel-Tuttle have remained remarkably constant in brightness over some tens of returns, with no evidence of noticeable fading. If comets indeed fade very slowly, then their active lifetimes may be quite long.

It thus appears extremely unlikely that 1996 PW could have evolved physically to a dormant or extinct state in the median dynamical age of only 28 returns, and unlikely at the 99% level that it could have done so in a physical lifetime of <800 returns. The estimated flux of long-period comets at Earth's orbit is ~10 yr^{-1} (Weissman 1996), suggesting ~25 yr^{-1} at 2.5 AU, the perihelion distance of 1996 PW (assuming a uniform cometary perihelion distribution vs. heliocentric distance; Everhart 1967). From our Monte Carlo simulation described above, we expect that 12% of the comets will be in orbits similar to that of 1996 PW (a = 200–500 AU). Combined with the physical lifetime estimate above, the expected flux of extinct long-period comets in such orbits with $q \leq 2.5$ AU is thus ~0.03 yr^{-1} or less.

Could 1996 PW be an asteroid that was ejected to the Oort cloud and that has now been thrown back into a planet-crossing orbit? Although there has been some speculation on asteroids being placed in the Oort cloud (Wood 1979; also Oort 1950, although that suggestion was likely based on a poor understanding of the icy nature of comets and of the heliocentric temperature profile in the planetary region), accepted models of solar system formation suggest that the vast majority of Oort cloud objects are comets that originated in the Uranus-Neptune zone (Fernandez & Ip 1981; Duncan, Quinn, & Tremaine 1987). The problem of Oort cloud asteroids has never been pursued in detail.

However, new dynamical simulations by Levison & Duncan (1997b), shown in Figure 2, find that 8% of material initially in orbits between Jupiter's orbit and 3.3 AU (roughly the outer edge of the main asteroid belt) is ejected to bound orbits with $a > 5 \times 10^3$ AU, i.e., in the Oort cloud. The numerical integration included the gravitational effects of the Sun and four giant planets. It did not include the effects of galactic tides or passing stars and thus should be considered preliminary. The trajectory of a particle was followed until it was ejected from the solar system, impacted the Sun or a planet, or reached an orbit with an aphelion distance $\geq 10^4$ AU, at which point it was

TABLE 1
PROBABLE ANNUAL FLUX

Origin	Flux (yr^{-1})
Extinct long-period comet	$<3.6 \times 10^{-2}$
Oort cloud asteroid	$>2.9 \times 10^{-2}$
Extinct ecliptic comet	5×10^{-5}
Main belt asteroid	$<4 \times 10^{-5}$
Trojan asteroid	3×10^{-5}

NOTE.—Probable annual flux of objects in orbits similar to that of 1996 PW, assuming different origin scenarios, and normalized to a semimajor axis range of 200–500 AU and a perihelion distance of less than 3 AU.

assumed to enter the Oort cloud. Earlier crude integrations by Duncan et al. (1987) found capture probabilities for objects initially in the Jupiter-Saturn region similar to the 8% used here.

Given an initial surface density of condensed solids, i.e., rocky/carbonaceous bodies, in the solar nebula of 15 g cm^{-2} at Earth's orbit, and assuming that the surface density varied as $r^{-3/2}$ through this region (Weidenschilling 1997), there would have been 3.2 Earth masses ($M_{\oplus}$) of rocky/carbonaceous bodies between 3.3 and 5.2 AU. If half of this material was ejected, and 8% of the ejected material went into the outer, dynamically active Oort cloud, then one would expect 0.13 $M_{\oplus}$ of asteroids in the outer Oort cloud. This compares with a total cometary mass of ~16 $M_{\oplus}$ originally in the outer, dynamically active Oort cloud, assuming a current population of 10^{12} comets, a mean nucleus mass of 3.8×10^{16} g, and 40% of the original Oort cloud population surviving (Duncan et al. 1987; Weissman 1996). Thus, 0.8% of the objects perturbed back into the planetary system from the Oort cloud may be asteroids rather than comets, assuming that the size distributions are similar. We suggest that this is a conservative number since considerably more rocky objects must have been ejected from orbits interior to 3.3 AU during the dynamical clearing of the planetary zones.

Given the ratio found above and assuming a population of 10^{12} comets in the outer Oort cloud, then there are currently $\sim 8 \times 10^{9}$ asteroids in the outer cloud. Again, taking an estimated flux of ~25 long-period comets yr^{-1} at the perihelion distance of 1996 PW, and 12% of the objects in orbits similar to 1996 PW, predicts a flux of ~0.024 asteroids yr^{-1}, close to the flux of extinct long-period comets estimated above.

Note that the ratio of extinct comets versus asteroids from the Oort cloud is independent of the details of what we assume for the flux of long-period comets or their perihelion distribution in the planetary region, since we make the same assumptions for both populations. The critical parameters in determining the ratio are the active lifetimes of the long-period comets and the fraction of the Oort cloud population that is asteroidal.

A third explanation for the origin of 1996 PW is that it is an extinct ecliptic comet currently evolving out of the planetary system. Analysis of previous dynamical simulations of the evolution of ecliptic comets from the Kuiper belt (Levison & Duncan 1997a) finds that only 3×10^{-8} of the population will be found at any time in orbits with a = 200–500 AU and $q < 3$ AU, similar to that of 1996 PW. The total steady state population of ecliptic comets, given the observed population of active Jupiter-family comets, is estimated to be $\sim 10^{7}$ objects (Levison & Duncan 1997a). Thus, one would predict ~0.3 ecliptic comets currently in an orbit similar to that of 1996 PW. Assuming a 5900 yr orbital period, the flux of such objects is $\sim 5 \times 10^{-5}$ yr^{-1}.

Next, we consider whether 1996 PW could be an asteroid recently ejected from the planetary system by the Jovian planets. Approximately 2500 asteroids with diameters greater than 1 km are currently evolving out of the main asteroid belt (Menichella, Paolicchi, & Farinella 1996; D. Davis 1997, private communication). Based on dynamical simulations by Levison & Duncan (1997b) we estimate that less than 6×10^{-5} of these asteroids are expected to be in orbits similar to that of 1996 PW, or less than 0.2 objects. Assuming a 5900 yr period, the expected flux is less than 4×10^{-5} yr^{-1}.

Finally, ~1200 objects from the Jupiter Trojan asteroid clouds are estimated to be currently evolving out of the planetary system (Levison, Shoemaker, & Shoemaker 1997). Approximately 2×10^{-4} of these objects are expected to be in orbits similar to that of 1996 PW, or only ~0.2 objects. Assuming the orbital period of 1996 PW, the flux is $\sim 3 \times 10^{-5}$ yr^{-1}.

3. DISCUSSION

Our results are summarized in Table 1. We conclude that the most likely scenario for the origin of 1996 PW is that it is from the Oort cloud. However, we find that it is equally likely that 1996 PW is an extinct long-period comet or an asteroid. We favor the latter interpretation because of the conservative approach we have taken in estimating the number of asteroids in the Oort cloud and the likelihood that active physical lifetimes for comets are greater than 800 returns. We can remove those conservative assumptions and assume a 1600 return active lifetime for the long-period comets and that 4.5 $M_{\oplus}$ of asteroidal material initially between 1.0 and 5.2 AU was ejected from the early solar system (again assuming that accretion was 50% efficient). In that case the expected flux of extinct long-period comets in orbits similar to that of 1996 PW and with $q < 3$ AU drops to $\sim 1.8 \times 10^{-3}$ yr^{-1}, whereas the asteroidal flux from the Oort cloud increases to 8.1×10^{-2} yr^{-1}. The predicted fraction of the Oort cloud that is asteroids is 2.3%.

The asteroids were likely ejected to the Oort cloud early in the solar system's history during the clearing of the interplanetary zones. This asteroid, 1996 PW, has now been returned to the planetary region by the same combination of stellar and galactic perturbations that feed long-period comets in toward the Sun.

What is the future for 1996 PW? We integrated 24 test particles with initial orbits similar to 1996 PW, both forward and backward in time, until the objects were either ejected from the planetary system or perturbed to semimajor axes greater than 10^{4} AU, allowing them to be recaptured to the Oort cloud. The fraction of surviving objects versus time is shown in Figure 3. The median dynamical age at the time of loss was 80 returns with a typical lifetime of 7×10^{5} yr. This is somewhat longer than the expected dynamical lifetime for Jupiter-family comets evolving out of the planetary system (Levison & Duncan 1997a). Roughly half the objects are ejected to interstellar space, while the other half are returned to orbits in the Oort cloud. The shortest lifetime was 3×10^{5} yr, and the longest was 8.4×10^{6} yr.

Our results suggest that the process that ejected planetesimals from the primordial solar nebula sampled material from as close to the Sun as the asteroid belt, and thus objects with much warmer formation temperatures than previously thought. This diverse sample is now preserved in the Oort cloud and is slowly

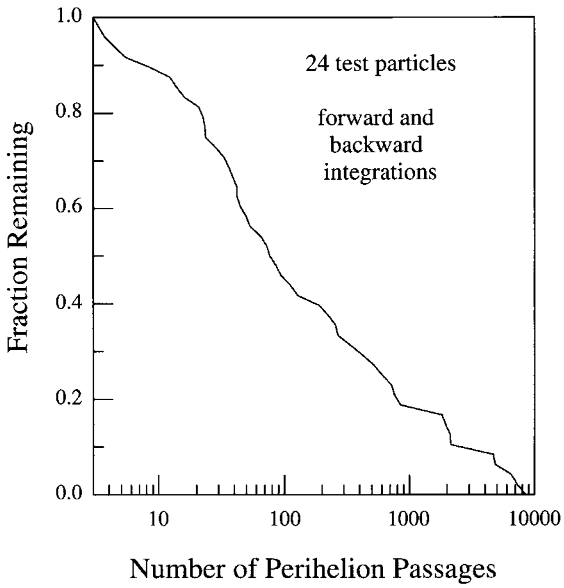

FIG. 3.—Dynamical lifetimes for 24 test particles in orbits similar to the current orbit of 1996 PW, integrated forward and backward in time. The median dynamical age is 7×10^5 yr, or about 80 returns.

fed back into the planetary system. The observed compositional differences among cometary nuclei (A'Hearn et al. 1995) are now more easily explained, because the ejection process appears to have sampled planetesimals from different temperature regimes throughout the planetary system.

Given the results above, we suggest that 1996 PW may be only the first detected member of a likely population of asteroids that are resident in the Oort cloud, some of which may now be passing through the planetary region on highly eccentric orbits. We note that two other asteroidal bodies, 5335 Damocles ($q = 1.6$ AU, $e = 0.866$, $i = 61\stackrel{\circ}{.}7$), which had been thought to be possibly an extinct cometary nucleus (Asher et al. 1994), and 1997 MD_{10} ($q = 1.5$ AU, $e = 0.943$, $i = 59\stackrel{\circ}{.}1$; Marsden 1997), may also be asteroids that have evolved inward from the Oort cloud, although their orbital periods are considerably shorter than that for 1996 PW. We hope that discoveries of this new class of solar system objects will increase as additional automated search programs such as the NEAT program on Haleakala and the Spacewatch program on Kitt Peak come on line.

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