DYNAMICAL EVOLUTION OF THE OORT CLOUD

Paul R. Weissman
Earth and Space Sciences Division
Jet Propulsion Laboratory
Pasadena, CA 91109 USA

ABSTRACT. New studies of the dynamical evolution of cometary orbits in the Oort cloud are made using a revised version of Weissman's (1982) Monte Carlo simulation model, which more accurately mimics the perturbation of comets by the giant planets. It is shown that perturbations by Saturn provide a substantial barrier to the diffusion of cometary perihelia into the inner solar system; Jupiter also. Perturbations by Uranus and Neptune are rarely great enough to remove comets from the Oort cloud, but do serve to scatter the comets in the cloud in 1/a. The new model gives a population of 1.8 to 2.1 x 10^{12} comets for the present-day Oort cloud, and a mass of 7 to 8 earth masses. Perturbation of the Oort cloud by giant molecular clouds in the galaxy is discussed, as is evidence for a massive "inner Oort cloud" internal to the observed one. The possibility of an unseen solar companion orbiting in the Oort cloud and causing periodic comet showers is shown to be dynamically plausible but unlikely based on the observed cratering rate on the earth and moon.

1. INTRODUCTION

Weissman (1982, hereafter referred to as Paper I) developed a new Monte Carlo simulation model for studying the dynamical evolution of comets in the Oort cloud under the influence of random stellar perturbations. By running a large number of hypothetical comets through the model, it was possible to test the dynamical plausibility of various theories of cometary origin. One of the more important results of Paper I was that the population of the Oort cloud had been depleted by between 30 and 84% depending on where in the primordial solar nebula the comets actually formed. Also, using the simulation model it was possible to calculate the population of the cloud and the distribution of orbital elements of comets in the Oort cloud, and to show that stellar perturbations had so randomized the cometary orbits over the history of the solar system that it was impossible to choose among several proposed formation sites for the Oort cloud comets.

The simulation model developed in Paper I assumed a relatively simple mechanism for perturbation of comets passing through the planetary region: comets approaching within 1.4 times the semimajor axis of Sat-

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urn's orbit had a 65% chance of being removed from the Oort cloud either by hyperbolic ejection or capture to a short-period orbit due to Saturn perturbations, and those approaching Jupiter's orbit had a 94% probability of removal. Comets which returned to the Oort cloud were assumed to have no change in their orbital energies, thus ignoring the small, but non-zero, perturbations by Jupiter and Saturn, as well as those by Uranus and Neptune. Perturbations by the two outer jovian planets are rarely great enough to remove comets from the Oort cloud, but can yield a significant change in semimajor axis, orbital period, and aphelion distance.

In the revised model presented here, the perturbations on the orbital energy of comets entering the planetary region, $q < 40$ AU, is chosen randomly from a gaussian distribution with rms value equal to the sum of the rms perturbation from each of the planets whose orbits were crossed. For Jupiter the rms perturbation is $620. \times 10^{-6}$ AU^{-1}, and for Saturn, Uranus, and Neptune the values are 101., 7.7, and 5.9×10^{-6} AU^{-1}, respectively. The new semimajor axis is then tested for hyperbolic ejection, an aphelion distance beyond the sun's sphere of influence (2×10^5 AU), or capture to a shorter period orbit ($P < 10^6$ years, $Q < 2 \times 10^4$ AU) where the comet is relatively unaffected by stellar perturbations. Comets which survive these end-states and are returned to the Oort cloud do so with the new, perturbed semimajor axis and continue to evolve until they fall into one of the possible end-states, or the total time followed exceeds the age of the solar system.

2. DYNAMICAL EVOLUTION OF COMETS

As in Paper I, the revised dynamical model was used to test different hypotheses of cometary origin. Initial perihelion distances of 20, 200, and 10^4 AU were chosen to represent cometary formation as icy planetesimals in the Uranus-Neptune zone, on the edge of the primordial solar nebula accretion disk, or in distant subfragments of the primordial nebula. The initial aphelion distance for all the orbits was chosen as 4×10^4 AU, and the total rms velocity perturbation on the Oort cloud over the history of the solar system was chosen to be 0.120 km s^{-1}. Cases were typically run for between 10^4 and 5×10^4 hypothetical comets.

The relative fraction of comets falling into each of four possible end-states: direct hyperbolic ejection, stellar loss (aphelion beyond 2×10^5 AU), planetary loss (ejection or capture due to planetary perturbations), and survivor is given in Table 1. These results are almost identical with those for similar cases described in Paper I, indicating that the previous, approximate treatment of planetary perturbations was acceptable. Thus, the major results of Paper I are validated. The lack of direct ejections by stellar perturbations is a result of a weakness in the dynamical model which emphasizes the sum of distant random perturbations, rather than the more violent though less frequent perturbations by stars passing directly through the Oort cloud.

A new result of the revised model is the ability to more accurately study the diffusion of cometary perihelia into the planetary region. The perihelion distribution of all new comets passing within 200 AU of the sun over the history of the solar system is shown in Figure 1. Pre-

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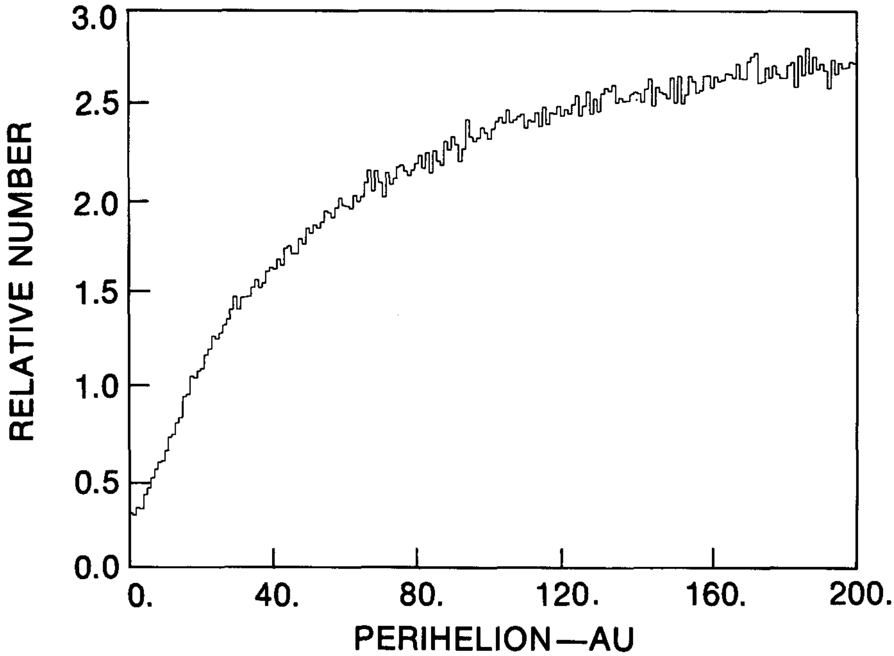

Figure 1. Perihelion distribution for new comets from the Oort cloud passing through the planetary region over the history of the solar system. The number of comets increases rapidly with increasing perihelion distance.

TABLE I. Oort Cloud End-States

End-state	Initial perihelion - AU		
	20	200	10,000
Planetary loss	0.773	0.477	0.076
Ejected	0.0	0.0	0.0
Stellar loss	0.068	0.068	0.214
Survivor	0.159	0.455	0.710

vious estimates of the perihelion distribution by Oort (1950) and Weissman (1980) predicted that it would be flat with increasing perihelion distance, while Kresak and Pittich (1978) believed it could be fit by $N(q) \propto q^{1/2}$. In fact, the number of comets per interval in perihelion distance increases only slowly in the observable region ($q < 5$ AU),

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then rises rapidly out to about 20 AU before beginning to level off and asymptoticly approach a maximum value about ten times that at 1 AU. The number of comets passing through perihelion is 1.5, 2.1, 3.6, and 5.0 times the value at 1 AU at the orbits of Jupiter, Saturn, Uranus, and Neptune, respectively. At 200 AU the flux of comets is 9.3 times the flux at 1 AU and still slowly increasing. This result was also demonstrated by Fernandez (1982).

To enter the observable region of the solar system, $q < 5$ AU, the comets must "leap frog" over the orbits of the outer planets, with some probability that they will be lost at each perihelion passage. Thus, the inner solar system is, in fact, undersupplied in new comets from the Oort cloud. Conversely, to account for the observed flux of new comets from the Oort cloud requires a larger total Oort cloud population. Following the method used in Paper I, the new population estimates from the revised dynamical model are shown in Table 2. As in Paper I, the different possible formation sites for the cometary nuclei all yield approximately the same current population estimate. The original population of the Oort cloud varies, however, based on the different depletion factors for the different origin hypotheses.

Also shown in Table 2 is the estimated mass of comets in the original and current Oort clouds. These estimates are based on the cometary mass distribution found by Weissman (1983) but using a revised value for the albedo of cometary nuclei surfaces. Weissman (1983) assumed an albedo of 0.6 based on observational results by Delsemme and Rud (1973). But laboratory studies of the albedo of dirty ice mixtures by Clarke and Lucey (1984) have shown that albedos between 0.1 and 0.3 are more likely to be expected. Using an assumed albedo of 0.3 raises the previous estimate of cometary masses in Weissman's paper by a factor of 2.8. These revised values are shown in Table 2.

The number of comets passing within 1.4 times the semimajor axis of each of the Jovian planets and their dynamical fate is shown in Table 3. Note, that although this particular case (initial $q = 20$ AU) followed 5×10^4 hypothetical comets, there are over 2.4×10^5 passages within the planetary region. Thus the average Oort cloud comet has possibly made between four and five passes through the planetary region, though fully 80% of them are through the Uranus-Neptune zone only. Note that Saturn actually removes slightly more comets from the Oort cloud than does Jupiter, because its lower removal efficiency is compensated for by a higher flux of comets crossing its orbit.

Lastly, the distribution of orbital elements for the hypothetical comets surviving in the present-day Oort cloud is shown in Figure 2. This, again, is for the case with initial $q = 20$ AU. Although the orbits all had the same initial energy, $1/a = 50 \times 10^{-6}$ AU^{-1}, and eccentricty, $e = 0.9990$, they have now diffused widely through the diagram to fill most of the possible orbits. The sharp cut-off of orbits along the left edge of the scatter diagram is the result of the limit on the sun's sphere of influence of 2×10^5 AU.

The especially dense band of comets extending down from the middle-top of Figure 2 towards the left are comets with aphelia of about 4.5×10^4 AU. Though the orbits in the cloud have been largely randomized, there appears to be some concentration close to the original aphelion

TABLE II. Oort Cloud Population and Mass

	Initial perihelion - AU		
	20	200	10,000
Current poulation - 10^{12}	1.8	2.1	1.9
Original population - 10^{12}	11.7	6.5	3.7
Current mass - earth masses	7.1	8.2	7.4
Original mass - earth masses	45.5	18.4	10.5

TABLE III. Comets Passing through the Planetary Region

	Planet				
End-state	Jupiter	Saturn	Uranus	Neptune	Total
Ejected	8899	8594	28	5	17526
Stellar loss	122	1021	202	86	1431
Captured	8749	9280	1104	556	19689
Returned	1056	9837	87449	108646	206988
Total	18826	28732	88783	109293	

distance, 4 x 10^4 AU. In reality the expected aphelion distribution of initial Oort cloud orbits would be some range of values, rather than the single one used in this test case, so the concentration shown in Figure 2 would not exist.

In general, the cometary aphelia tend to diffuse outward (towards the left in Figure 2) rather than inward. This results from the pumping up of orbital energy and angular momentum by the stellar perturbations, but is also a reuslt, in part, of limitations in the dynamical simulation model. Because the comets are typically in such long period, highly eccentric ellipses it is assumed that stellar perturbations occur at aphelion only. Future models will attempt to correct this deficiency.

3. PERTURBATIONS BY GIANT MOLECULAR CLOUDS

Clube and Napier (1982) suggested that the Oort cloud would be severely perturbed by random encounters with giant molecular clouds in the galaxy. They estimated that the solar system would have about 10 to

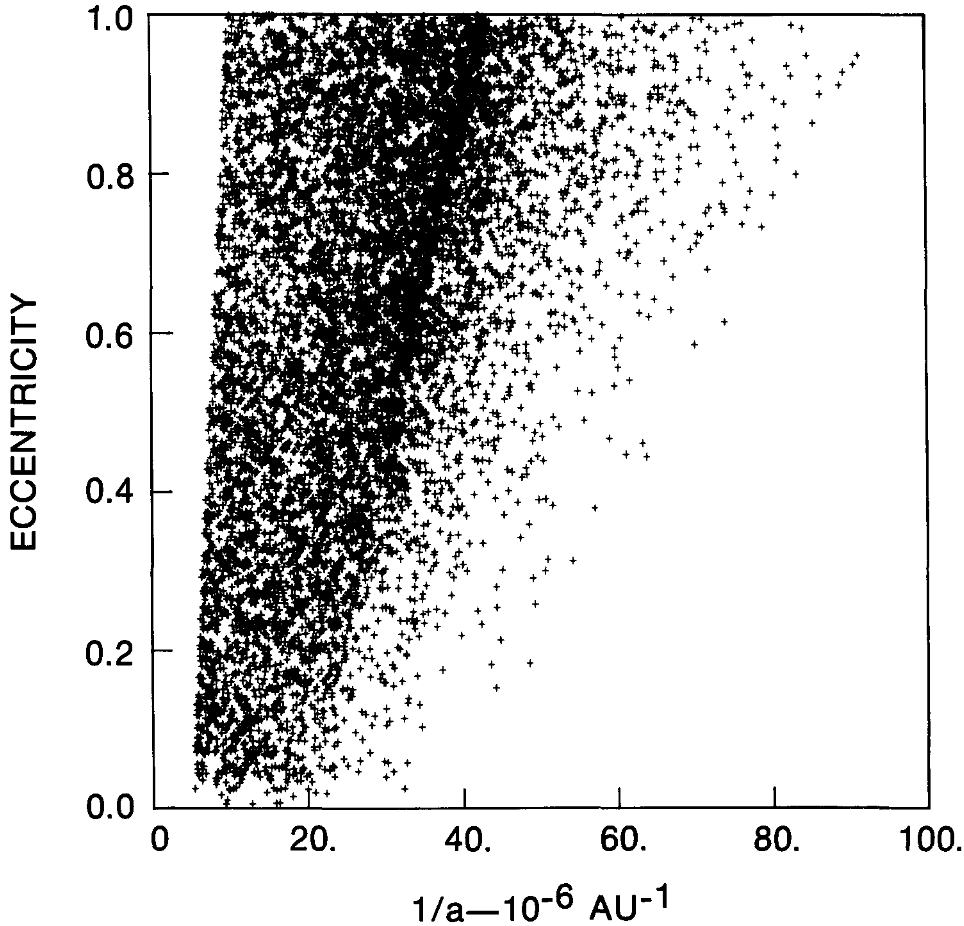

Figure 2. Scatter diagram in energy and eccentricity for the orbits of 7928 hypothetical comets in the current Oort cloud. The comet orbits have been randomized and have diffused widely away from their initial values of 1/a and eccentrictiy of 50 x 10^{-6} AU^{-1} and 0.9990, respectively. The sharp cut-off at the left is caused by the aphelion limit of 2 x 10^5 AU.

20 encounters with GMC's in its lifetime, and that the tremendous mass of the GMC's would strip away a major fraction of the comets in the cloud. They also suggested that the cloud was replenished by capturing large numbers of comets which were originally a part of the perturbing GMC.

An examination of Clube and Napier's ideas by Bailey (1983a) has shown that they overestimated the perturbations on the Oort cloud by a factor of between two and ten. The range in uncertainty is caused by our lack of knowledge of the sun's past dynamical history in the galaxy. The sun's current velocity relative to the Local Standard of Rest is about 16 km s^{-1}, as compared with typical values of about 60 km s^{-1} for G-type stars in the galaxy. If the sun has always had this relatively low velocity then the perturbations by the GMC's are reduced by only a factor of two, and are still a major problem. But if the current low velocity of the sun is only a statistical fluke, and its past velocity has been closer to the observed value for G-type stars, then the GMC's represent only a modest addition to the total perturbation from random passing stars.

Since the acceleration of random motions of stars during their lifetimes generally results from encounters with GMC's, the latter of the two alternatives described above is more likely the correct one. It would also be more likely from a statistical point of view.

Bailey also found that the distribution of observed cometary orbits was consistent with a "centrally condensed cloud" in which there was a signifcant number of comets interior to those actively being perturbed by passing stars. Clube and Napier (1984) found that such an "inner Oort cloud" could serve as a replenishment source for the outer, observable cloud after a catastrophic encounter with a GMC. This eliminated the difficulty of capturing comets from a GMC, typically encountered at a relatively high velocity, ~20 km s^{-1} or more.

The existence of a massive inner Oort cloud has been suggested for a number of other reasons. Shoemaker and Wolfe (1984) believe that planetesimals scattered out of the Uranus-Neptune zone would form such an inner cloud and account for the late heavy bombardment of the terrestrial planets and Jovian satellite systems. Cameron (1978) has suggested that such an inner cloud would come from icy planetesimals formed in a primordial solar nebula accretion disk extending out to 10^3 AU or more. Fernandez (1980) has shown that such a cloud would be a more efficient source for the short-period comets, and both Whipple (1964) and Bailey (1983b) have suggested that a comet belt or cloud beyond Neptune could explain the perturbations on Uranus's orbit.

An inner Oort cloud would be difficult to sense dynamically because the aphelia of the comet orbits would be too small, $< 10^4$ AU, for them to be significantly perturbed by random passing stars, and the perihelia would be beyond the orbit of Neptune. Hills (1981) suggested that stars passing particularly close to the sun would perturb the inner cloud and send showers of comets into the planetary region perhaps once every 5×10^8 years.

Bailey (1983c) calculated that the thermal radiation of comets in the inner cloud might be detectable using the Infrared Astronomical Satellite (IRAS), and Low et al. (1984) have reported that IRAS observed unexplained emission which they interpret as clouds of cold material in the outer solar system. Weissman (1984) interpreted the IRAS observations of clouds of fine particulate material around Vega and some 30 other stars in the solar neighborhood as the dust from inner Oort clouds around each of these stars.

4. UNSEEN SOLAR COMPANIONS IN THE OORT CLOUD

Whitmire and Jackson (1984) and Davis et al. (1984) suggested that a small, unseen companion star to the sun is in a distant orbit which

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periodically takes it through the denser regions of the Oort cloud. Although this companion star must be of low mass and luminosity to have escaped detection, its low orbital velocity makes it a very significant perturber. According to the authors above, the companion star perturbs the inner cloud and causes periodic comet showers which eventually result in catastrophic biological extinctions on the earth. They suggest that the star has a period of 2.8×10^7 years to match the estimated periodicity in the extinctions found from paleontological records.

The stability of a star in such a distant orbit can be studied using the revised Oort cloud simulation program described in this paper. According to the authors above, the perihelion of the companion star is about 3×10^4 AU, giving an aphelion distance of 1.55×10^5 AU to yield the correct orbital period. Five thousand hypothetical stars in such an orbit, randomly oriented on the celestial sphere, were integrated through the revised model.

It was found that 23% of the stars failed to survive for ten orbits, the estimated number of observed cycles of extinction in the fossil record. Most of those lost diffused to aphelia beyond the sun's sphere of influence, a likely result considering the large initial aphelion. Continuing the integration further, 86% of the stars failed to survive for more than 10^9 years. Additionally, the orbital period of some stars which remained bound tended to oscillate considerably, the average period change per orbit being on the order of 10%.

In conclusion, one can not exclude the possibility of such a star remaining bound to the sun in a reasonably constant period orbit during the recent past, but the dynamical simulation results suggest that it is far from a certainty. The probability is small that the star should be in just such an orbit at this point in the solar system's history if it formed concurrently with the planetary system.

A more conclusive argument against the existence of an unseen companion star involves the observed cratering record on the earth and moon. Current estimates of the mean cratering rate in the terrestrial region based on craters counted on dated surfaces is in rough agreement with that expected from the observed flux of earth-crossing comets and asteroids. Repeated comet showers would result in far more craters, between 5 and 18 times the current number (depending on the assumed mass distribution for cometary nuclei) if the companion star had been in the same orbit over the history of the solar system.

Assuming that the companion star has evolved outward from a more tightly bound initial orbit does not alleviate this problem; it in fact makes it worse since the shorter initial orbital period would result in more frequent comet showers. The only apparent solution is to assume that the companion star was captured relatively recently, about $3 - 5 \times 10^8$ years ago. The probability of a capture event is very low, on the order of 10^{-13} per star passage. Still, comet showers over only that recent interval may be enough to double the total cratering on the earth and moon in the past 4×10^9 years. That result would be incompatible with the presently estimated cratering rate from dated craters.

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DISCUSSION

Fernandez: Have you computed the perturbations caused by the hypothetical solar companion on the Oort cloud?

Weissman: I have only done some very preliminary runs with one of my Monte Carlo simulation programs and it seems that an unseen solar companion would be very damaging to the Oort cloud, removing perhaps 10% of the comets on each orbit. It is difficult to estimate this accurately because the impulse approximation used in the program is not valid when the star's velocity is so low. To do it correctly requires a detailed integration of the orbits.

Lissauer: Will the magnitude of Nemesis' perturbations of the Oort cloud comets vary greatly from orbit to orbit?

Weissman: Yes. The perihelion of the star's orbit random walks up and down which would greatly vary the number of comets showering from the inner Oort cloud into the planetary region. This fact has been used by Hut to explain why some extinctions are more catastrophic than others.

Bailey: Can you comment on the increase in the rate of perihelion passages versus perihelion distance found by yourself (factor ~ 10) and the last speaker, Fernandez (factor ~ 100)?

Weissman: Fernandez follows the comets throughout their lifetimes while I terminate my runs sooner, when the comets can no longer be considered part of the Oort cloud. Comets with perihelia in the Uranus-Neptune zone continue to survive for many additional returns because of the relatively small perturbations in 1/a caused by those planets.