DYNAMICAL EVOLUTION OF THE OORT COMETARY CLOUD

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The dynamical evolution of comets in the Oort cloud under the influence of stellar perturbations has been modeled using Monte Carlo techniques. It is shown that the cloud has been depleted over the history of the solar system. Comets are lost from the cloud by direct ejection due to close stellar encounters, diffusion of aphelia to distances beyond the sun's sphere of influence, or diffusion of perihelia into the planetary region where Jupiter and Saturn perturbations either eject them on hyperbolic trajectories or capture them to short-period orbits. The population of the cloud is estimated to be 1.0 - 1.5 x 10^{12} comets and the total mass is on the order of 1.9 earth masses. In addition to random passing stars, less frequent encounters with giant molecular clouds may play a significant role in randomizing the orbits of comets in the cloud and reducing the effective radius of the sun's sphere of influence.

1. Introduction

Oort (1950) proposed that the solar system is surrounded by a vast reservoir of 1.8 x 10^{11} comets whose orbits are controlled by perturbations from random passing stars and whose aphelia extend roughly halfway to the nearest stars. The hypothesis has been successful in explaining the distribution of original inverse semimajor axes, $1/a_0$, for the long-period comets.

The distribution of observed long-period comets in $1/a_0$ and perihelion distance, q, is shown in Figure 1. The Oort cloud is visible as a horizontal band of comets at near-zero $1/a_0$. Dynamically "new" comets from the Oort cloud enter the solar system and are perturbed by the planets, either diffusing upward in the diagram to short-period orbits, or being ejected on hyperbolic orbits. For perihelia greater than about 2.8 AU only Oort cloud comets are observed, probably because they are anomalously bright at large solar distances due to highly volatile materials in the outer layers of their nuclei. The few comets in the figure with initially hyperbolic orbits are not truly extra-solar comets but most likely the result of errors in the orbit calculations.

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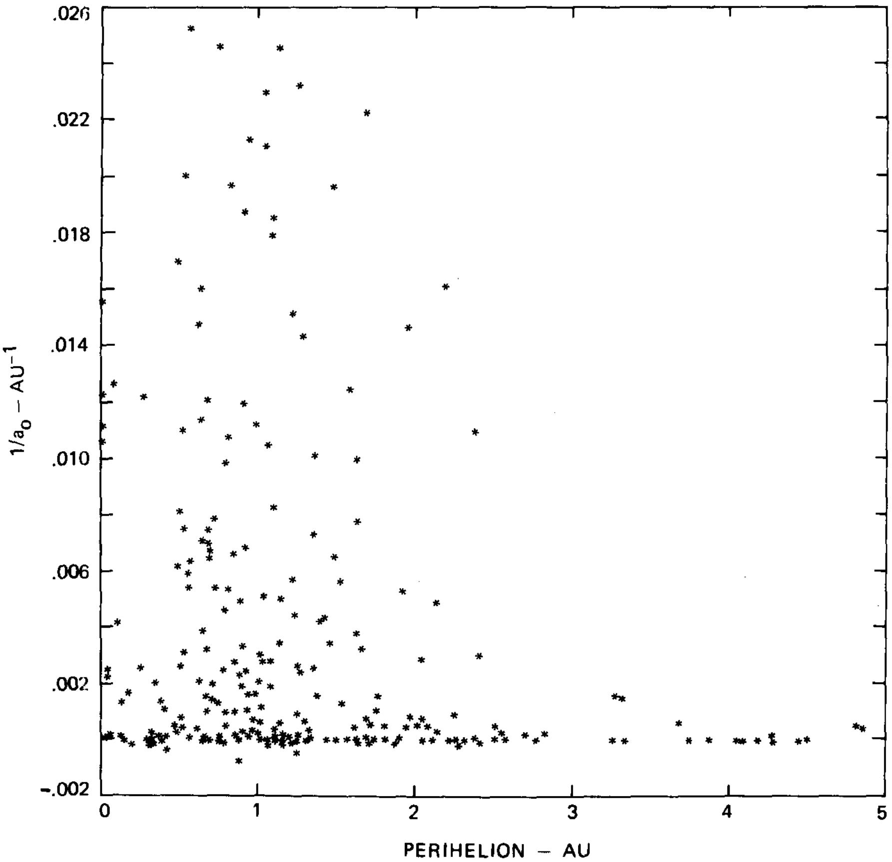

Figure 1. Scatter diagram in original inverse semimajor axis and perihelion distance for the observed long-period comets. The Oort cloud is the horizontal band of comets at near-zero but slightly positive $1/a_o$.

Although the dynamical evolution of long-period comets once they enter the planetary region has been studied in some detail, relatively little work has been done on the evolution of orbits in the Oort cloud. Analysis of the perturbations on the cometary orbits can yield insights into the number and mass of comets in the cloud, the distributions of orbital elements, and even possibly clues to the origin of the comets and the Oort cloud. This work reports results for a new dynamical model of the cloud using Monte Carlo simulation techniques.

2. The Dynamical Model

Weissman (1980) developed a statistical model of stellar perturbations where the change in velocity of a comet orbiting in the Oort cloud is given by

$$\Delta V_{rms} = 1.7 \times 10^{-3} \, T^{1/2} \text{ m/s} \quad (1)$$

where T is the period of the orbit in years. For the new computer model stellar perturbations were simulated as a single perturbation applied at aphelion of each orbit. The perturbation velocity was chosen randomly from a Maxwell velocity distribution whose rms value was given by equation (1), and whose direction was randomly oriented in space.

After each perturbation new orbital elements were calculated and then tested for several possible end-states. These included ejection on a hyperbolic orbit (referred to as "ejected" below), diffusion of aphelia to a distance beyond the sun's sphere of influence: 2×10^5 AU ("stellar loss"), or diffusion of perihelia into the planetary system where perturbations by Jupiter and/or Saturn will either capture the comets to short-period orbits or eject them from the solar system ("planetary loss"). There also is a finite probability that the planets could return the comets to the Oort cloud. If the comets did not fall into any end-state the cycle was repeated until they did, or until 4.5×10^9 years had passed (referred to as "survivor" below). No physical loss mechanisms were assumed to operate in the Oort cloud.

The numerical simulation model was typically run for samples of 10^4 hypothetical comets. Initial orbits were chosen to represent various theories of cometary origin: either formation in the Uranus-Neptune zone with subsequent ejection to the cloud, or origin _in situ_ in satellite subfragments of the primordial solar nebula. Cases were run to examine the effect of varying the initial perihelion or aphelion distance, and the total statistical perturbation from passing stars. A more complete description of the model and cases run is given in Weissman (1982a).

3. Results

The first set of cases were run for a range of perihelion distances between 20 and 10^4 AU. The initial aphelion distance was chosen to be 4×10^4 AU and the total velocity perturbation was 120 m/s. The fraction of comets lost to each of the possible end-states are shown in Table 1. Also shown is the mean $1/a_0$ of new comets entering the planetary region during the last 5×10^8 years of the evolution.

It is seen that only between 16% and 70% of the initial cloud population survives after 4.5×10^9 years. The greatest depletion is for

Table 1. Oort Cloud End-States

Initial perihelion (AU)	20	100	200	10^3	2×10^3	10^4
Ejected	0.0	0.0	0.0	0.0	0.0	0.0
Stellar loss	0.009	0.024	0.033	0.051	0.073	0.212
Planetary loss	0.834	0.609	0.520	0.313	0.222	0.075
Survivor	0.157	0.367	0.447	0.636	0.705	0.713
$1/a_0$ of new comets (10^{-6} AU^{-1})	42.	42.	42.	42.	41.	38.

the case of comets originating in the Uranus-Neptune zone; cometary perihelia rapidly diffuse back into the planetary region where Jupiter and Saturn perturbations eject them. For larger initial perihelia the number of comets lost to the planetary end-state decreases and those lost by diffusion of aphelia to distances beyond the sun's sphere of influence increases. Also, the fraction of survivors increases with increasing initial perihelion distance.

The lack of a significant number of direct ejections from the Oort cloud is likely a product of deficiencies in the perturbation model. Weissman (1980) showed that about 9% of the cloud population would be lost due to close encounters with stars passing through the cloud. Apparently the Maxwell velocity distribution is not a good representation of the stellar perturbations for the very close encounters.

Analysis of the rate of cloud depletion with time shows that there is a very rapid re-introduction of comets into the planetary region for the case of origin in the Uranus-Neptune zone, with a flux of up to 200 times the current cometary flux. This may provide a source for the late heavy bombardment of the terrestrial planets. For larger initial perihelion distances variations in the flux rate are less pronounced.

The simulation model can also be used to estimate the total population of the Oort cloud. Everhart (1967) has estimated the flux of long-period comets (brighter than $H_O = 11$) after correction for observational selection effects as ~16 comets/AU/year. About 20 to 25% of these are new comets from the Oort cloud. Using these figures and the results from the numerical simulation model one finds the current and original Oort cloud populations shown in Table 2.

The population estimates are about five to eight times Oort's original estimate of 1.8×10^{11} comets. This results because of the increased estimate for the cometary flux over the figure used by Oort. Revising Oort's estimate based on Everhart's flux gives a current population of 1.3×10^{12} comets. The original population of the cloud varies between 1.5 and five times that figure, depending on at what distance from the sun the comets formed.

Weissman (1982b) has used Everhart's (1967) derived brightness distribution for the long-period comets to find the mass distribution of the cometary nuclei. Based on an Oort cloud population of 1.4×10^{12} comets brighter than $H_O = 11$, he finds a total cloud mass of 1.15×10^{28} grams, or about 1.9 earth masses.

Table 2. Current and Original Population of the Oort Cloud

Initial perihelion (AU)	20	100	200	10^3	2×10^3	10^4
Current population (10^{12} comets)	1.0	1.3	1.2	1.0	1.3	1.4
Original population (10^{12} comets)	6.3	3.4	2.7	1.7	1.7	2.0

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Another possible result from the Monte Carlo model is the distributions of orbital elements in the Oort cloud. The stellar perturbations cause the orbits to diffuse in perihelia, aphelia, and energy. It is found that over the history of the solar system the stellar perturbations tend to randomize the orbits in the cloud, leaving little evidence of the original orbits or clues to the formation sites for the cometary nuclei. This fact is also reflected in the population estimates in Table 2, where the different initial perihelia cases all yield approximately the same current number of comets in the Oort cloud.

Additional cases of the simulation model were run to examine the effects of varying the initial aphelion distances and the total stellar perturbations. It was shown that stellar loss became an increasing important end-state as aphelion increased and hence, initial binding energy decreased. For initial aphelia greater than about 1.2×10^5 AU no comets survived after 4.5×10^9 years. Increasing the total stellar perturbation also tended to increase the fraction of comets lost to stellar loss while having little effect on the planetary end-state. For comets with initial aphelia of 4×10^4 AU, none survived when the total statistical perturbation exceeded 260 m/s.

4. Discussion

The results of the Monte Carlo simulation model show that the Oort cloud has been randomized by stellar perturbations over the history of the solar system and that a significant fraction of the original population has been lost to a number of dynamical end-states. The randomization of orbits has made it difficult to determine the original cometary orbits and thus gives few clues as to where the comets may have formed.

Estimates for the total number and mass of comets in the cloud are consistent with current theories of solar system origin and thus again do not allow one to discriminate between cometary formation among the outer planets, on the edge of the solar nebula, or in satellite fragments of the solar nebula, as has been suggested by different authors.

One problem with current models of the Oort cloud is that the dynamical radius found from theoretical studies is about twice that derived for the observed orbits of new comets. Marsden et al. (1978) found a mean $1/a_o$ of 46.3×10^{-6} AU^{-1} for 61 Oort cloud comets, corresponding to a mean aphelion distance of 4.32×10^4 AU. This is to be compared with typical estimates of the dynamical limits on the cloud based on stellar perturbations of 10^5 AU or more. This discrepancy suggests the existence of some additional perturber(s) on the cometary orbits.

Recently, Clube and Napier (1982) have suggested that the Oort cloud is periodically stripped away by perturbations from close encounters with giant molecular clouds (GMC's). At the same time, Clube and Napier claim that the solar system captures interstellar comets from the GMC's to form a new Oort cloud. They suggest that this may have happened on the order of 12 to 25 times over the history of the solar system.

Though Clube and Napier have likely identified the missing perturber, it is also likely that they have overestimated the effect of GMC's on the Oort cloud. Their work tends to emphasize low velocity encounters between the solar system and GMC's. Though such encounters can indeed be catastrophic, they are also exceedingly rare. Also, their use of two-body hyperbolic encounter dynamics to describe the passage of the solar system near a GMC probably oversimplifies the relative Keplerian motion of bodies in orbit about the galactic nucleus and moving through the "lumpy" gravitational field of the galaxy's spiral arms. A further problem is their lack of a mechanism for repopulating the cloud. Valtonen and Innanen (1982) have demonstrated that the typical capture probability for an interstellar comet is on the order of 10^{-13}.

Another problem is the uncertainty in the current knowledge of the mass, space density, and dynamics of GMC's in the galaxy. They are a relatively new development in galactic astronomy and it may be unwise to give too much credibility to speculations about the consequences of their existence until the state of knowledge about GMC's has matured somewhat more.

Clube and Napier have clearly raised an interesting question with regard to the present understanding of the dynamical history of the Oort cloud. Future modeling of the cloud dynamics must consider the effect of GMC's, and future increases in our knowledge of GMC's will be most valuable in improving the accuracy of such models. However, at present Clube and Napier have not provided conclusive arguments for their hypothesis. It remains for future studies to determine whether or not they are right.

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DISCUSSION

NAPIER: On Dr. Weissman's comment that the figures we have assumed are exaggerated: the data for molecular clouds we have used come from Burton and Liszt and if you want to dispute those you will have to argue with them. On the encounter speeds it is true that Napier and Staniucha used lower encounter speeds but this was because the strong gravitational focussing of large masses ($M \sim 5.10^5\ M_0$) tends to pull the sun in when its speed is preferentially low. In the current presentation ($M \sim 2.10^5\ M_0$) we use the same typical encounter speeds as those used by Weissman, Oort, and others.

The Valtonen and Innanen capture probability, $\propto 1/v^7$, refers to Jupiter capture which is very inefficient. Recent work (Valtonen, unpublished) shows that $10^{10} - 10^{12}$ comets can easily be captured, $\propto$ (v km/s/20)^3, going through a field of comets $\sim 10^{-2}/AU^3$. Capture of Oort clouds is therefore unavoidable if you accept the Copernican principle and that there are regions of dense star formation ($10^3 - 10^4$ Trapezium stars within a few pc) through which the sun will sometimes pass.

WEISSMAN: Many of the problems I see with Clube and Napier's work involve small errors or differences in judgement, none of which alone would discredit the work, but the total sum of which leads me to seriously doubt its conclusions. The mass, space density, and velocity of GMC's used in Clube and Napier are certainly within the ranges suggested by other investigators, but values could just as easily have been chosen from the same ranges that would not lead to disruption of the Oort cloud. Until today's presentation the emphasis of all the papers published has been on low velocity encounters, ~ 5 to 10 km/s, again clearly overestimating the effect of the GMC's. With regard to any new capture mechanism by Valtonen, I would be most interested to see this work and would hope that it soon appears in the literature. However, we agree that his earlier paper (with Innanen) clearly showed that capture of interstellar comets through Jupiter perturbations is a very unlikely event.

DELSEMME: Depending on the different theories of origin, shouldn't we find in <u>some</u> cases a rather large residual rotation momentum of the Oort cloud, due either to the depletion mechanism and/or proposed replenishment, that would be linked either to the ecliptic plane (protoplanetary origin) or to the galactic plane (galactic origin)? Statistics of "new" comets are poor because they deal with small numbers, but an asymmetry of more than 10% is clearly not observed. This could rule out <u>some</u> of the theories of origin.

WEISSMAN: There is an ongoing debate over whether the Oort cloud is spherically symmetric or whether asymmetries in the perihelion directions of cometary orbits are observed. Such claims of the existence of asymmetries are usually linked to the solar apex direction and are taken as support of Lyttleton's theory of cometary origin. As you say, the observed level of asymmetry is small and is subject to small number statistics. I see no reason why the sun's relative motion among the neighboring stars could not introduce a preferential component in the random stellar perturbations, that would then be detected as an apparently asymmetric distribution of cometary orbits entering the planetary region. Also, it is possible that the observed asymmetry is an observational selection effect resulting from seasonal variations in the discovery rate of new comets.

As to the question of residual angular momentum from some cometary origin, there is still some uncertainty whether stellar perturbations would totally randomize orbital inclinations in the Oort cloud over 4.5 x 10^9 years. The presence of GMC's will certainly help speed this randomization process. The lack of any well observed asymmetries in the Oort cloud is an argument against Clube and Napier's hypothesis, since their recently captured cloud would not have had sufficient time to be randomized. If disruptive encounters with GMC's occur with a frequency of once every 3 x 10^8 years, then there should still be a strong residual anisotropy in the observed orbits of new comets from the Oort cloud. This is clearly not seen.

NOTE ADDED IN PRESS: Dr. Valtonen has been kind enough to send me a preprint of his new paper on cometary capture. The only capture mechanism he finds which can possibly support the Napier-Clube hypothesis requires an unseen solar companion of 0.1 $M_\odot$ at 10^4 AU from the sun. Though such an object has been occasionally suggested in the literature, its existence remains a matter of conjecture only. Even then, Valtonen's capture mechanism falls almost two orders of magnitude short of the current Oort cloud population estimates given in this paper. Also, Valtonen requires a rather high density of interstellar comets in the encountered GMC. These results cast considerble doubt on Napier and Clube's suggestion that the Oort cloud is a recently and repeatedly captured object.