PHYSICAL AND DYNAMICAL EVOLUTION OF LONG-PERIOD COMETS

Paul R. Weissman
Department of Earth and Space Sciences
University of California, Los Angeles, CA 90024
and
Jet Propulsion Laboratory
Pasadena, CA 91103

Oort (1950) first suggested that the source of the long-period comets is a large spherical cloud of comets surrounding the solar system and extending roughly halfway to the nearest stars. The observational evidence for this is the distribution of original inverse semi-major axes of the long-period comets which shows a large spike of comets at very small positive values of $1/a_o$, less than 10^{-4} AU^{-1}. Attempts to model the evolution of these comets by Oort in his original paper, by Kendall (1961), Shteins (1961), and Whipple (1962) were successful in recreating the general shape of the $1/a_o$ distribution. However in each case the authors were unable to match the observed ratio of new comets from the Oort cloud versus older comets evolving under the influence of planetary perturbations.

The work described here is a further study of the problem using a new method, a Monte Carlo simulation of the evolution of the long-period comets under the influence of a combination of physical and dynamical processes. Models were derived for the perturbation of cometary orbits by the major planets, by non-gravitational forces, and by random passing stars. Physical loss of comets due to planetary collision, random disruption (splitting), and loss of all volatiles was also modeled. These processes were combined in a computer simulation program which followed large numbers of hypothetical comets as they evolved from the Oort cloud to their eventual end-states. By changing input parameters to the computer program it was possible to vary the relative effect of each of the different processes.

In the case of planetary perturbations 5×10^4 hypothetical comets were integrated through a model solar system consisting of Jupiter and Saturn. The results were tabulated and used to derive the probability density function for the total change in $1/a$ per perihelion passage as a function of the perihelion distance and inclination of each comet. The density function was fit with a Gaussian distribution whose standard deviation was given by a second order polynomial expansion in q and $\cos i$. For comets with perihelia uniformly distributed between 0.01 and 4 AU and with random inclinations, the standard deviation was

R. L. Duncombe (ed.), Dynamics of the Solar System, 277–282.

https://doi.org/10.1017/S0074180900012869 Published online by Cambridge University Press

721×10^{-6} AU^{-1}.

Non-gravitational forces were studied using the model of Marsden et al. (1973). The change in 1/a was found for hypothetical comets passing through the solar system on parabolic orbits with non-gravitational accelerations similar to those measured for some real comets. It was found that non-gravitational changes in 1/a could exceed that due to planetary perturbations, particularly for comets with $q < 1$ AU. Also, if it was assumed that the orientation of the rotation axes of the cometary nuclei did not change from one perihelion passage to the next, then the non-gravitational forces could cause a regular stepping of the comets in 1/a, rather than the randomly positive or negative steps as a result of planetary perturbations.

For stellar perturbations a model similar to that by Wyatt and Faintich (1971) was used. Stellar perturbations were treated as a random perturbation in the aphelion velocity vector of each comet's orbit, dependent on the period of the orbit, and were only really important for comets with large aphelion distances, greater than about 10^4 AU.

A simple model for planetary collision showed that the probability of a random long-period comet passing within the Roche limit of a planet or colliding with an asteroid was 1.35×10^{-7} per perihelion passage. This was negligible compared to other loss mechanisms and was not included in the final version of the simulation program. A study of the statistics of observed splits of long-period comets yielded a disruption rate of 10% per perihelion passage for Oort cloud comets and 4% for older comets making subsequent returns. Except for four tidal splittings the disruption events appear to be random with respect to perihelion distance, inclination, time of splitting, etc. The lifetime of one kilometer radius water ice spheres in near-parabolic orbits was found as a function of perihelion distance in terms of the number of perihelion passages made, using a modification of the method described by Lebofsky (1975). This served as the basis for a model of cometary lifetime against loss of all volatiles.

The processes described above were combined in a Monte Carlo simulation program. In addition to being able to vary the effect of each of the processes, the program also incorporated several different initial perihelion distributions. Weissman (1977) has shown that the expected perihelion distances of Oort cloud comets are uniformly distributed with respect to q in the planetary region. However in running the simulation program it was found that a better fit to the observed results was obtained by using a perihelion distribution heavily skewed towards small perihelia orbits, much like the observed perihelion distribution for all long-period comets. This tended to compensate for observational selection effects in the data.

The program also allowed the user to vary the location of the source of the long-period comets. It was clearly demonstrated that the only way to achieve the observed $1/a_o$ distribution was to place the source at an aphelion distance of 2×10^4 AU or more, yet still gravitationally bound to the solar system. Thus the basic correctness of the Oort hypothesis was confirmed.

Initial runs with the simulation program using the nominal models for each of the processes described above gave a significantly better fit to the observed $1/a_o$ distribution than any of the previous studies. There were several reasons for this. First, due to the work of Everhart and Raghavan (1970) and Marsden et al. (1978) the catalog of observed original orbits has been significantly improved over past catalogs and a prior bias towards Oort cloud comets has been largely removed. Secondly, the random disruption rates used in the model, based on 24 observed disruption events, are significantly higher than those used in previous studies, in particular the 10% disruption rate for Oort cloud comets. Lastly the inclusion of the dependence of the planetary perturbations on perihelion distance and inclination, combined with the skewed initial perihelion distribution, is a better physical representation of the evolution of the long-period comets which are actually observed.

A comparison of the observed and computer generated $1/a_o$ distributions is shown in table 1. The observed distribution is based on the orbits of 184 selected comets and has been smoothed over varying intervals of $1/a_o$ and normalized so that the height of the Oort cloud spike is unity. The one standard deviation statistical error associated with each interval is also given. Two computer generated distributions are shown, the first for the nominal model that has already been described and the second for an improved model discussed below.

Table 1. Observed and modeled $1/a_o$ distributions.

$1/a_o$ range - 10^{-6} AU^{-1}	Nominal model	Improved model	Observed
0 - 100	1.0	1.0	1.0
100 - 500	.108	.098	.104 ± .025
500 - 1000	.103	.088	.067 ± .017
1000 - 2000	.077	.058	.037 ± .009
2000 - 4000	.043	.027	.023 ± .007
4000 - 6000	.022	.014	.013 ± .004
6000 - 8000	.013	.010	.012 ± .004

Although the fit to the $1/a_o$ distribution was substantially improved using the nominal model, the perihelion distribution resulting from it did not agree with the observed orbits. The simulation program was unable to account for the observed rapid disappearance from the solar system of small q comets with a < 400 AU. At the same time the model did not allow a sufficient number of intermediate q comets to evolve to orbits with small semi-major axes, as is observed. To study this various modifications to the nominal models were proposed and explored with the Monte Carlo program. Three major changes came out of this exercise. First, it was shown that a process similar to loss of volatiles but acting much more rapidly could account for the loss of small q comets. Whipple (1977) has suggested that as ice sublimates from a comet's surface a crust of silicate materials is left behind which halts further sublimation and renders the comet unobservable. Tests with the simulation program showed that a crust forming after 50 to 100 meters of water ice had been removed could account for the disappearance of small q comets at the required rate.

Second, it was demonstrated that the disruption probability can not be the same for all comets but must vary with some comets being highly susceptible to disruption and others relatively immune. As a first order improvement tothe nominal model the comets were split randomly into two groups: the first with a constant disruption probability and the second with zero disruption probability. The best fit to the observed $1/a_o$ and q distributions was obtained with 15% of all comets having zero disruption probability and the remainder having a probability of splitting of about 12% per perihelion passage. An additional change in the model to fit the observed statistics was that the difference in disruption probability between Oort cloud and older comets tended to disappear, nearly equal disruption probabilities being required for each group.

Finally, the effect of non-gravitational perturbations was greatly reduced. It would appear that this process is more random in nature than the model derived for it would indicate.

In addition to the improvement in the perihelion distribution of the comets, the improved model yielded a better fit to the observed $1/a_o$ distribution. This can be seen in table 1. The $1/a_o$ distribution for the improved model (unsmoothed) is shown in figure 1, based on 10^5 hypothetical comets followed for a maximum of 10^3 returns each with the Monte Carlo simulation program. Each interval in the histogram has a width of 10^{-4} AU^{-1}.

The primary end-states found for the long-period comets with the improved model were: ejection on hyperbolic orbit, 65.2%; random disruption, 27.6%; and formation of silicate crusts, 7.1%. Other significant end-states were capture to short-period orbit, 0.04%; and perturbation to a perihelion distance less than the solar Roche limit, 0.02%. The average comet made 4.4 perihelion passages with a mean time of 5.9×10^5 years between its first perihelion passage from the Oort cloud and the one which determined its particular end-state. The mean hyperbolic excess velocity for the ejected comets was 0.60 km/s.

This work has attempted to explore the various hypotheses concerning the origin of the long-period comets and to assess the relative role played by various physical and dynamical processes in the evolution of the comets. Though the solution found is not necessarily unique, it

https://doi.org/10.1017/S0074180900012869 Published online by Cambridge University Press

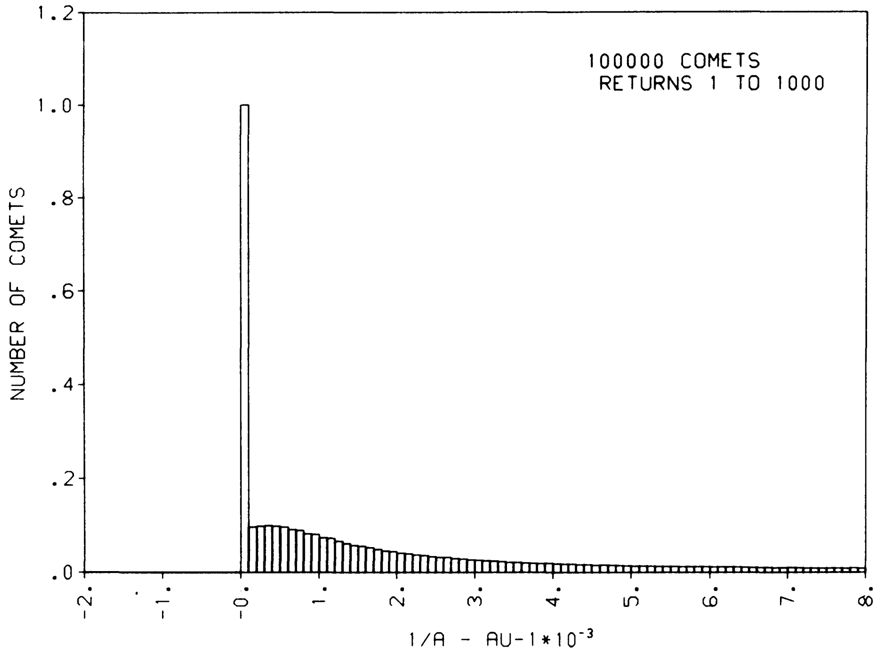

Figure 1. Computer generated $1/a_o$ distribution based on 10^5 hypothetical comets.

does identify the major processes which control the long-period comets and describes their histories and likely end-states.

The work described here is part of the author's doctoral dissertation in planetary and space physics at the University of California. The author wishes to thank his advisors, George Wetherill and William Kaula, for their guidance and their support during the course of this study. This work was supported in part by NASA grant NGL 05-007-002.

Everhart, E., and Raghavan, N.: 1970, "Astron.J." 75, 258.
Kendall, D.G.: 1961, "Fourth Berkeley Symposium on Mathematical Probability and Statistics" Univ. Calif. Press, 3, 99.
Lebofsky, L.A.: 1975, "Icarus" 25, 205.
Marsden, B.G., Sekanina, Z., and Yeomans, D.K.: 1973, "Astron.J." 78, 211.
Marsden, B.G., Sekanina, Z., and Everhart, E.: 1978, "Astron.J." 83, 64.
Oort, J.H.: 1950, "Bull.Astron.Inst.Neth." 11, 91.
Shteins, K.A.: 1961, "Soviet Astron.J." 5, 228.
Weissman, P.R.: 1977, "Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins" Univ.Toledo Press, 87.
Whipple, F.L.: 1962, "Astron.J." 67, 1.

Whipple, F.L.: 1977, "Center for Astrophysics preprint" No. 814.
Wyatt, S.P., and Faintich, M.B.: 1971, "Bull.Am.Astron.Soc." 3, 368.

DISCUSSION

Kiang: I would like to point out that, at least for comets like P/Halley, the effect of persistent, nongravitational force is in most cases absorbed into a hyper period through the stabilization of the system by the Jovian perturbation. Detail in Paper VI.8.

Weissman: Marsden, Sekanina, and Yeomans have shown that the non-gravitational perturbations seen in some long-period comets are an order of magnitude or more greater than those seen in short-period comets. These perturbations would in fact dominate the motion of the small perihelion comets if they were regular, greatly exceeding the effects of the random planetary perturbations in most cases.

Yabushita: Your calculated 1/a distribution: does it refer to a fixed value of N (perihelion passage) or to a fixed interval of time after cometary formation?

Weissman: The calculation assumes a continuous flux of comets from the Oort cloud and the resulting distribution is the steady state $1/a_o$ distribution. It is essentially the sum of $1/a_o$ distributions for all values of N from 1 to 1000.

https://doi.org/10.1017/S0074180900012869 Published online by Cambridge University Press