# SECTION I

# ORIGIN OF COMETS

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# THE ORIGIN OF COMETS AMONG THE ACCRETING OUTER PLANETS

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ABSTRACT. The hypothesis of formation of comets as an accompaniment to formation of Uranus and Neptune from icy planetesimals is attractive for several reasons, but has suffered from long-standing problems regarding formation of the planets themselves. The history of this *problem is reviewed, and recent results are described that may help* solve it. Numerical simulations of planet growth show that when the system of planetesimals is no longer artificially constrained to a power-law size distribution, growth of planets may occur in reasonable time. An adequate number of comet-sized bodies to populate the Oort cloud is not produced as collisional debris during the planet-building process. Rather, the comets are probably a remnant of the original planetesimal "building blocks" from which the planets grew.

The origin of the Oort Cloud of comets was likely to have been connected with the formation of planets in the solar system. Nebular densities beyond the planetary system were probably too low to have permitted accretion of comet-sized bodies (Öpik 1973, Safronov 1977a). But closer to the sun, planet formation was apparently accompanied by production of smaller bodies, some of which would necessarily be perturbed by planetary encounters into orbits in the Oort Cloud. Thus, comets are a plausible by-product of planetary formation.

In the context of the planetesimal hypothesis of planet formation, it seems plausible that comets are planetesimals that were removed to the Oort Cloud by close encounters with growing (or nearly grown) planetary embryos before they could be accreted. For a number of reasons, the most promising candidate region for cometary origin is the Uranus-Neptune zone. Uranus and Neptune are quite likely to have been formed from icy planetesimals. Moreover, Uranus and Neptune's sizes and positions are appropriate for having scattered residual planetesimals out to the Oort Cloud with reasonable (~10%) efficiency (Fernandez and Ip 1981, Safronov 1969). From closer to the sun, it was much harder to scatter planetesimals out that far. After Jupiter's sudden increase in mass with gas accretion around its solid core



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(Safronov and Ruskol 1982), it became too effective at scattering planetesimals; most were ejected from the solar system on strongly hyperbolic trajectories, with only a very small fraction contributing to the Oort Cloud region. Closer to the sun, planetesimals were rocky, not icy, and hence not the source population for comets.

While the evidence has pointed to cometary origin near Uranus and Neptune, quantitative analysis has awaited resolution of a fundamental problem regarding formation of the planets themselves: Accretion models (e.g., Safronov 1969) generally required $\sim 10^{11}$ yr for outer planet growth, assuming a plausible surface density of the planetesimal swarm of $\sigma \sim 0.3$ gm/cm$^2$. The slow growth was due to the increase in relative velocities among planetesimals believed to accompany growth of the planetary embryos, which kept gravitational cross-sections small.

Attempts to modify the theory to accommodate the actual existence of the outer planets involved ad hoc assumptions of either very high surface density of the planetesimal swarm or lower values of relative velocities among planetesimals. Levin (1972) considered the implications of increasing $\sigma$ one-hundred-fold to 30 gm/cm$^2$. Availability of so much mass increased accretion rates so as to give growth in $<10^9$ yr. But the excess material needed to be removed, and to eject so much material would require great loss of angular momentum from the planets. Levin pointed out that an implication is that Uranus and Neptune would have had to have formed ten times farther from the sun than their present orbits. With $\sigma$ thus $\sim 30$ gm/cm$^2$ at >200 AU, the total nebular mass would have had to have been $\sim 2\ M_{\odot}$, which as Levin concluded is much too large to be consistent with the planetesimal model of planet growth.

Safronov considered the possibility that growth rates were enhanced by a combination of high $\sigma$ and low velocities. The latter help by increasing gravitational cross-sections and thus speeding accretion. With $\sigma \sim 3$ gm/cm$^2$, the extreme problems noted by Levin are avoided. Safronov offered speculative suggestions as to why relative velocitkes might have been lower than for his nominal model, which was based on an assumed equilibrium between collisional damping and gravitational stirring by mutual encounters and which gave relative velocities on the order of the escape velocities of the larger bodies. Those suggestions included the following: (a) Relative velocities were distributed over some range of values. The segment of the population with higher velocities was preferentially ejected from the system, leaving only the low velocity portion of the population (Safronov 1969). (b) The low strength of icy planetesimals might have given a steep size distribution which yields lower relative velocities (Safronov 1972).

There are problems with both those ideas. Suggestion (a) raises questions about other planets' growth. For example, for the Earth, would such a low velocity component speed growth relative to the growth rate computed by Safronov based on the average velocity? Suggestion

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(b) is contradicted by experimental evidence (e.g. Hartmann 1969) which indicates that weak materials do not have such steep distributions; they simply break up more easily. Safronov (1977b) later suggested that gravitational instabilities directly produced large embryos, thus by-passing much of the evolutionary time required for collisional accretion. However, as described below, it is implausible that the gravitational instability could have produced such large bodies.

Levin (1978) suggested that relative velocities may have been lower than in Safronov's nominal growth models for another reason. He invoked Safronov's own dynamical theory in pointing out that velocities would be low compared with the escape velocity of the largest body, when in the late stages the planetary embryos "ran away" in terms of growth from the remaining planetesimal distribution in its zone. Once an embryo becomes detached from the continuous part of the size distribution, relative velocities no longer increase with the embryo's size.

In fact, more recent numerical simulations (Greenberg et al. 1978) of planet growth show that the size distribution may have been very different than assumed in Safronov's theory. For the terrestrial planets, most of the mass remained in small planetesimals (original building blocks plus a power law distribution of smaller debris), which damped velocities as the embryo grew. Velocities did not increase directly with embryo size. Growth of a substantial embryo was $\sim 10^{2-3}$ times faster than in Safronov's model. Qualitatively, such simulations, applied to the outer solar system, were expected to solve two problems, yielding (a) planets in reasonable time, and (b) a large reservoir of small bodies available for removal to the Oort Cloud.

In order to apply such simulations to the outer solar system we first needed to select plausible initial conditions. The conventional theory of gravitational instability in a flat dust disk (Safronov 1969, Goldreich and Ward 1973) predicts that the first generation of planetesimals at a given heliocentric distance is characterized by sizes proportional to $\sigma$, yielding radii >60 km. It seemed reasonable, based on the numerical results for terrestrial planet growth, that with this initial size the outer planets could have grown quickly, and that the comet-size bodies (1 to 10 km) would be produced as collisional debris.

Numerical simulations have now been applied to outer planet growth (Greenberg et al. 1984). We modeled accretion of solid icy material in Neptune's zone for cases with $\sigma$ in the range of 0.3 gm/cm$^2$ (near the minimum to form the planet) to 3 gm/cm$^2$. Initial planetesimals were given the characteristic size, produced by gravitational instability, corresponding to the value of $\sigma$, with initial relative velocities on the order of their escape velocities. In these simulations, the Neptune embryo grew rapidly, reaching 10% of its final mass in $\sim 10^8$ yr, at which time it is growing at a rate such that full size would be reached in $<10^9$ yr. Most of the mass remained in bodies of the original size, but collisional debris extended down through the cometary size range. The quantity of comet-sized debris is comparable to

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the estimated number of Oort Cloud comets ($\sim 10^{10}$ of $\sim 10$ km, $3 \times 10^{12}$ of $\sim 1$ km), but not enough to account for the order of magnitude loss in transporting them to the Cloud. After $10^{8}$ yr, the number of comet-sized bodies decreased as they were rapidly broken into even smaller pieces. This problem remained even when we modeled the bodies as being as strong as solid rock (impact strength $10^{8}$ ergs/cm$^{3}$).

Even if the initial population is taken to include in addition the required number of comet-size bodies, the presence of a comparable mass of 100 km bodies is sufficient to raise relative velocities enough to destroy the comet-size bodies before Neptune grows large enough to scatter material to the Oort Cloud. Neptune does grow rapidly, however, because, as in the earlier experiments, relative velocities are much less than the embryo's escape velocity.

The implication of our numerical experiments is that an adequate comet-size population can exist long enough for the Neptune embryo to reach scattering size only if such a distribution exists from the beginning and if there is initially a negligible mass contribution from bodies $\gtrsim 10$ km. Such an initial population consists of smaller bodies than predicted by the conventional gravitational instability models, even for the minimum $\sigma$ needed to make Neptune. However, such instability models assume that $\sigma$ refers to a dust layer of uniform density settling homologously to the plane of the nebula. In a non-uniform layer, gravitational instability occurs in regions that exceed a critical density. Thus clumping into planetesimals may begin even before all material has settled to the midplane.

We have modeled the earlier settling process, and find that if coagulation among dust grains occurs, larger grain aggregates experience runaway growth and rapid settling, forming a dense sub-layer in the central plane. This sub-layer may reach the critical density for instability while containing $\lesssim 1\%$ of the total mass of solids. The resulting planetesimals are correspondingly small; their actual sizes depend on the rate at which mass arrives at the central plane relative to the growth time of instabilities ($\sim$ the orbital period). Gravitational encounters among this first generation of bodies stir them out of the plane on the same time scale, but their perturbations do not affect later settling dust which is damped by gas drag. The process may repeat for several generations, while collisional accretion proceeds. A comet-like size distribution, rather than bodies $\gtrsim 60$ km, is a reasonable outcome of the gravitational instability process.

Numerical simulation of planet growth with this comet-size initial population in the outer solar system shows that growth of substantial planetary embryos occurs in very short time (see Fig. 1). A sufficient population of the comet-sized bodies remains to account for population of the Oort Cloud by scattering as the planetary embryos approach full size. The embryo is sufficiently detached from the size distribution that subsequent final accretion should be fairly fast. This model seems to satisfy all of our requirements.

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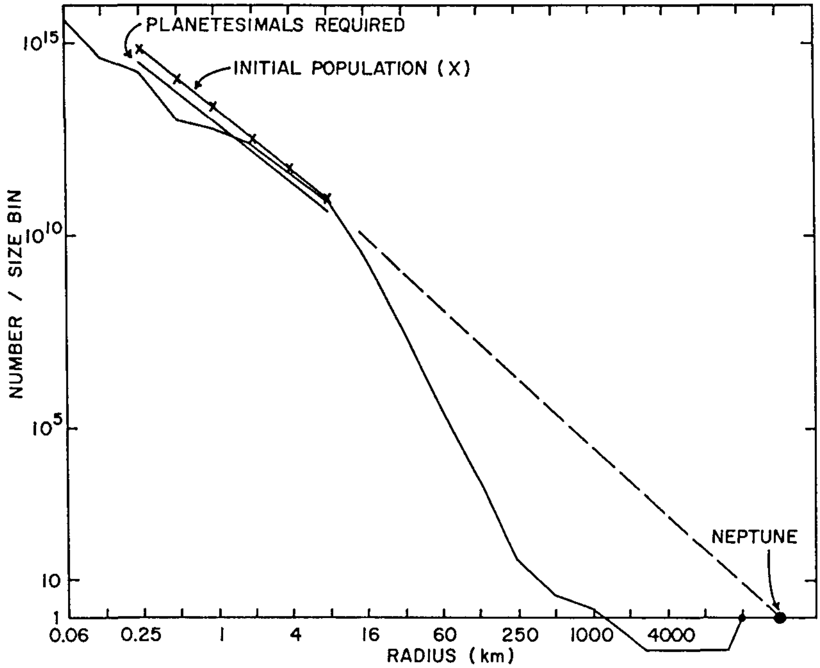


Figure 1: Evolution of a population of initially comet-sized bodies, shown by x's. The solid curve shows the population after $1.4 \times 10^5$ yr. For reference, the dashed line represents the slope for equal mass per size bin (factor of 2 in radius), and the uncompressed size of Neptune is shown. The line labelled "Planetesimals Required" shows the number of comet-sized bodies needed to account for populating the Oort Cloud with 10% efficiency (Fig. from Greenberg et al. 1984).

However, evolution beyond the stage shown cannot be modeled adequately by our numerical simulation in its present form, because a number of late-stage effects are not readily incorporated into our particle-in-a-box statistical approach. The dominance of a single body would make certain regions (e.g. the neighborhood of its own orbit) special. Also in the late stage questions arise as to the validity of computing gravitational cross-sections using the two-body encounter model. Because our model is not applicable to the late stage, there remain important questions about late-stage growth. Do the first-formed embryos accrete or scatter the small bodies between their orbits, or, alternatively, do many additional embryos grow among the first-formed ones, only later to be consolidated into a few planets? Similar questions remain regarding late-stage planet growth in the inner solar system.

Nevertheless, combining the results of our models for mid-plane settling and for outer planet growth, strongly suggests that comets are a representative residue of the initial population of planetesimals in the outer solar system, not fragments of larger bodies. At the very least, these results demonstrate that the long-standing problems with time required for outer-planet growth are not as serious as previously thought.

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## DISCUSSION

P. Farinella: How are your collisional accretion models affected by changing parameters like impact strength, fraction of kinetic energy going into fragments, etc.?

R. Greenberg: The basic conclusions are not affected by such choices. We have experimented with a wide range of assumed impact parameters. Interestingly, we find the greatest success in producing and preserving comet-size planetesimals when the material is assumed to be very strong. At first I was surprised by that result because I had expected that weaker material would tend to produce comet-size fragments more easily. From our numerical experiments, though, I learned that weak material tends in fact to be easily ground down to sub-comet-sized bodies; the runs which produced the most comets assumed strengths equal to that of strong rock or even iron!

J. Lissauer: Could you get more comet-sized bodies by ejecting them before they can get "ground down"?

R. Greenberg: Velocities are too small for ejection during the stages modeled in our numerical simulations; however, this process may be relevant later on.

B.A. Lindblad: Does it follow from your work that a significant amount of comets would at the present time be moving in nearly circular orbits between Uranus and Neptune?

R. Greenberg: That does not follow from our work, because we have not studied the late stage of planet growth. However, there may be some small zones of stability between the planetary orbits.

A. Fernandez: Have you considered how the possible migration of the accreting proto-Uranus and proto-Neptune, due to the exchange of angular momentum with planetesimals, might affect your model parameters; for instance, the surface density $\sigma$, the size range of formed planetesimals, and the total mass required to form Uranus and Neptune?

R. Greenberg: This may be a way for the planetary embryos (or protoplanets) to move through the zones that otherwise would be relatively isolated between the embryos' orbits. It could be a solution to some of the questions about late-stage evolution that I have raised. However, we have not yet examined the late stage in any detail.

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M.E. Bailey: You mentioned that Levin's suggestion of increasing $\sigma$ by increasing the mass of the solar nebula went agaiost the spirit of the planetesimal hypothesis. What is the largest mass nebula that is consistent with this scheme of things?

R. Greenberg: Usually the planetesimal hypothesis assumes a nebula mass ~5% of the sun's mass, while the "giant gaseous protoplanet" hypothesis assumes the total mass (sun + nebula) to be ~$2M_{\odot}$. One could imagine intermediate cases, which might have hybrid processes, but such models have not been studied.

P. Weissman: I have two comments: first, in answer to Dr. Lindblad's question, we would expect 0.5 - 1.0% of Uranus-Neptune zone planetesimals to be surviving in Uranus-Neptune-crossing orbits. Objects such as Chiron are almost certainly Uranus-Neptune planetesimals evolving dynamically out of that zone, as shown by Scholl.

Secondly, the distribution of cometary magnitudes found by Everhart after corrections for observational selection has a knee in the curve at about $H_{10} \simeq 6$. If one goes through the steps of converting the distribution to a distribution of cometary masses, we find that for a reasonable albedo, say 0.3, the size of the comets at the knee is about 8 km. Thus, we may ave observational confirmation of the type of size distribution you are talking about here.