67. THE ORIGIN OF COMETS

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Abstract. The evolution of the solar system is surveyed, it being presumed that the Sun, Jupiter, and Saturn formed rather quickly and essentially with the composition of the original collapsing cloud of dust and gas. Just as the refractory material of the cloud is considered to have formed into planetesimals, from which the terrestrial planets collected, so is the icy material supposed to have produced comets, or cometesimals, from which Uranus and Neptune (and to some extent Saturn and Jupiter) were built up. The presence of a residual belt of comets beyond the orbit of Neptune is discussed, analysis of possible perturbative effects on P/Halley indicating that the total mass of such a belt at 50 AU from the Sun could not now exceed the mass of the Earth.

Fig. 1. The Trifid Nebula (Lick Observatory).

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I shall deal only with a few aspects of the evolution of comets and of the solar system in order to point out a certain effect which may or may not be observable. I hope that you will look for it.

My basic assumption will be the usual one, namely that the solar system developed from a collapsing cloud of dust and gas. This is consistent with the earliest hypotheses of modern science – those of Kant and Laplace and with the concepts of Otto Schmidt.

I do not know whether the Trifid Nebula (Figure 1) represents the type of dust and gas cloud from which the solar system evolved, but it gives us some confidence that such condensations are not rare and isolated events.

The cloud is assumed to collapse because of instability, starting from a dimension of perhaps a large fraction of a parsec, and perhaps it would eventually look like the classical Laplacian discus (Figure 2). It is presumed to be a cool gas-dust nebula. One of the major problems, which we cannot discuss, is the rate of radiation loss against the energy gained by gravitational collapse. But presumably the gas in the outer regions cools after it collapses and takes the form of a Laplace-type discus.

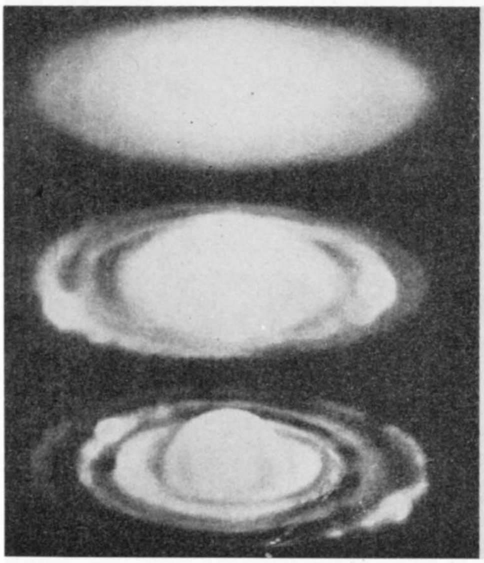

Fig. 2. The Laplace nebula concept.

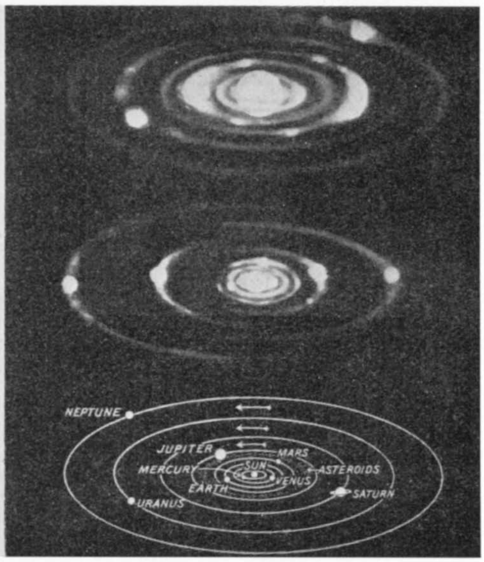

Fig. 3. The Laplace solar-system formation concept.

Of course, we well know that Laplace's concept of rings being left behind (Figure 3) is not acceptable in terms of modern dynamics. We cannot get involved in details of these problems. Let us start with the concept that the solar system bodies were accumulated from the condensation of dust and gas, the Sun developing at the center.

Comet 1957 V Mrkos (Figure 4) typifies the comets, which I believe are aggregates collected from material frozen out of the original gas and dust cloud at large distances from the Sun.

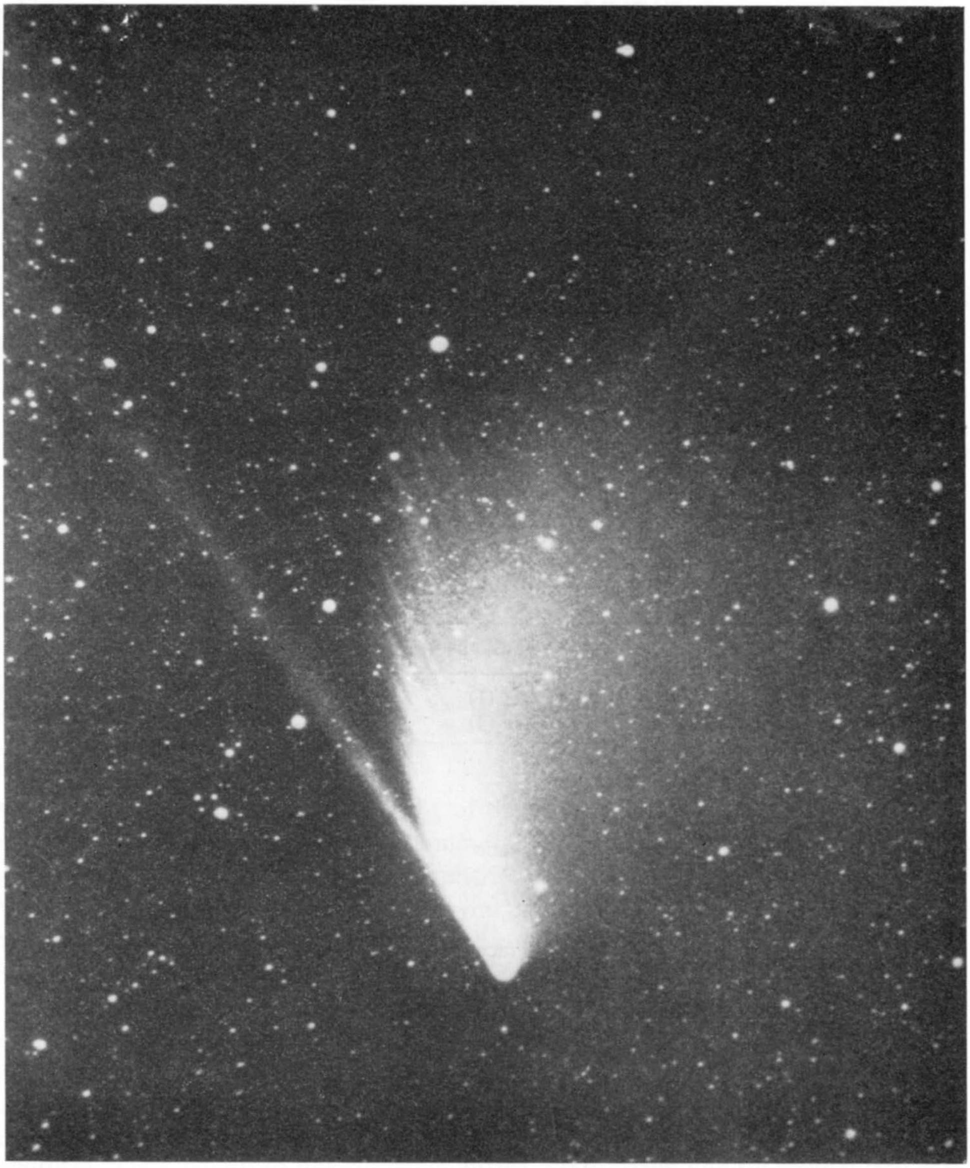

Fig. 4. Comet 1957 V Mrkos (A. McClure).

The chemical elements and compounds observed in comets are listed in Table I. It is clear that most of the gases are simple compounds of carbon, nitrogen, oxygen, and hydrogen. But a comet close to the Sun gives evidence of other heavier atoms when the solar heat is great enough to vaporize them.

Harrison Brown was perhaps the first to point out clearly that the bodies in the solar system may be subdivided according to three natural divisions among the physical characteristics of the chemical elements: the *earthy* materials such as iron, silicon,

TABLE I

Comets, observed composition

Head:	C_2, C_3, CH, CN, C^{12}, C^{13}
	NH, NH_2, [O I] OH, H
	Na, Si, Ca, Cr, Mn, Fe (Ni, Cu)
Tail:	CH^+, CO^+, CO_2^+, N_2^+, OH^+ (CN)
	and meteoritic dust

and magnesium that melt at rather high temperatures (see Table II); *icy* material which boils at rather low temperatures (and generally melts below 0 °C); and thirdly the *gases*, particularly hydrogen, helium, and the noble gases, that remain gaseous to extremely low temperatures. I question that at any time in the history of the solar system the temperature dropped low enough to freeze hydrogen and helium, because of the difficulty of radiating away the energy of collapse. Thus solid hydrogen or helium should not be among the icy materials that froze to form the comets.

TABLE II

Relative abundances of various atoms in the solar system[a]

Class of matter	Gaseous	Icy	Earthy
Elements and atomic weights	H (1) He (4)	C (12) N (14) O (16)	Mg (24) Si (28) Fe (56) etc.
Sun	1.0	0.015	0.0025
Terrestrial planets and meteorites	Trace	Trace	1.0[b]
Jupiter	0.9	0.1	Trace
Saturn	0.7	0.3	Trace
Uranus, Neptune and comets	Trace	0.85	0.15

[a] By mass.
[b] Including oxygen.

Now, if we look at the composition of bodies in the solar system (Table II), we see that, as presumed, the Sun is typical of the material with which we started. Among the terrestrial planets we find nearly 100% earthy materials and oxides with high melting points.

Jupiter has almost solar composition, perhaps 90% gaseous material and 10% ices. So it must have collected initially from material very much like the Sun itself. It naturally follows that Jupiter must have formed rather quickly with almost the original composition of the gas-dust cloud. But the terrestrial planets, forming within Jupiter's orbit, must have collected, as suggested by many people, particularly Chamberlain and Moulton, from planetesimals made of the refractory materials – the earthy materials.

Next we note that Uranus, Neptune and the comets, insofar as we know, have almost exactly the same composition. Thus I maintain, as do Kuiper, Cameron, and others, that Uranus and Neptune were built up in the same fashion as were the terrestrial planets, except that the building blocks in the outer part of the system, where the temperature was colder, were comets, not planetesimals; we might say *cometesimals*.

I suggest that Saturn was formed almost simultaneously with Jupiter but, being farther out from the Sun, it collected a greater fraction of comets to increase its icy composition to perhaps 30% in mass.

Because of the relative abundances of the gases, ices, and earthy materials, the various classes of bodies in the solar system require approximately the same minimum quantity of original material (see Table III). In the case of the terrestrial planets one

TABLE III

Minimum original planetary masses

Objects	Present mass (Earth = 1)	Factor	Original material (Sun = 1)
Terrestrial	1.9	500	0.0028
Jupiter	317	10	0.0095
Saturn	95	30	0.0086
Uranus and Neptune	32	75	0.0072
Comets	1	900	0.0027
Minimum original mass	—	—	0.0308

must throw away all but perhaps 0.2% of the material in the form of gas and ices. Without going into detail, one needs a minimum of about one percent of the original solar mass to form respectively the terrestrial planets, Jupiter, Saturn, Uranus and Neptune and the comets separately. As you can see, I leave out of consideration a huge number of processes, all of which are controversial, interesting and important. But I go now to my main point, which may possibly be settled observationally.

In my view then, as the solar system developed, the comets formed beyond Saturn and collected as cometesimals into Uranus and Neptune. When Uranus and Neptune were formed, their masses perturbed the motions of the remaining comets in this region of the solar system. Many of the comets were thrown into the inner part of the solar system where some were captured by the planets (particularly Saturn) and the Sun, some were sublimated by solar heat as they are today, and some were thrown to infinity. Others were thrown to great distances in elongated orbits and formed the present-day comet cloud, whose stability was first discussed by Öpik and later by Oort, the great comet cloud extending to many thousands of astronomical units from the Earth. The remainder should have been formed very nearly in, and not have deviated far from, the plane of Jupiter or the other planets. They should still be moving in nearly circular orbits and should correspond at great distances, i.e., beyond Neptune, to the asteroids between Mars and Jupiter (see Figure 5). They would be comets, not asteroids, occupying this region of space. But they cannot be observed

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directly as comets, nor by total reflected light from the Sun, nor by obscuration of stars. So without sending space probes to that region of the space I think it is hopeless to observe such comets directly, in case they do exist.

But they should have a gravitational effect and their mass might amount to the order of the Earth's mass! If there is indeed a comet belt beyond Neptune, it would perturb the motions of the outer planets and may have produced the perturbations in the motion of Neptune that have been attributed to Pluto (Whipple, 1964). We know that

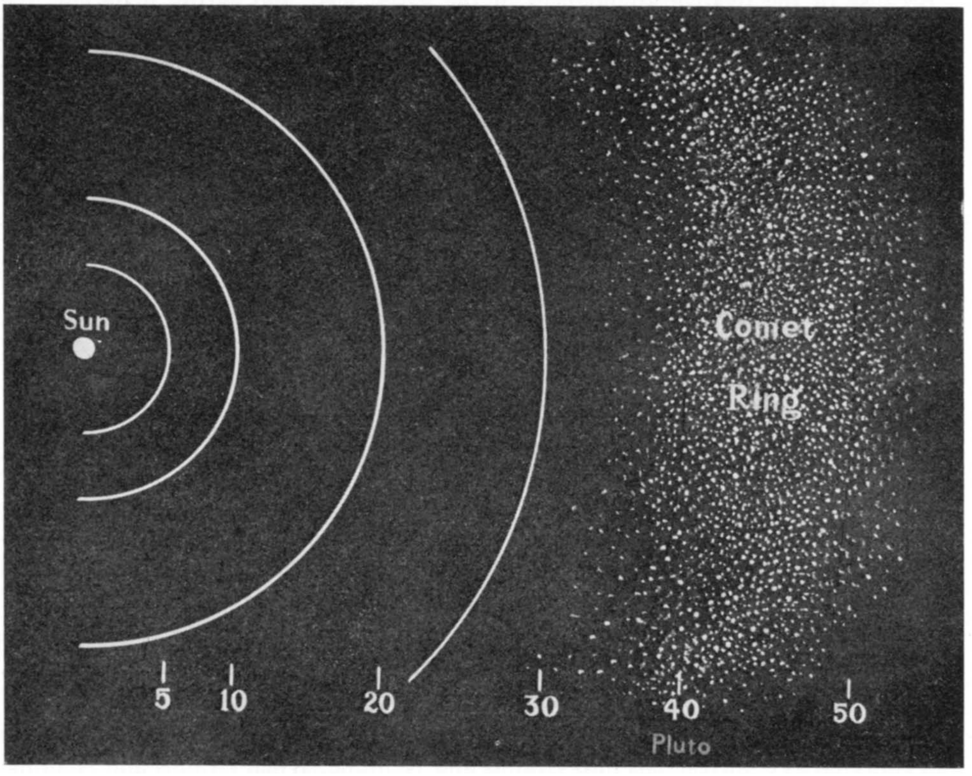

Fig. 5. Region of possible comet belt.

Pluto could not have a mass of the order of one Earth's mass; it must be very much smaller and could not have appreciably perturbed Neptune.

Figure 6 shows the poles of the ecliptic, of the invariable plane, of Saturn's orbit, of Jupiter's orbit, and of Neptune's orbit. If the pole of the comet belt is somewhere in the general direction indicated in Figure 6, it could then produce the perturbations in the latitude of Neptune that were attributed to Pluto. And the mass required would be inversely proportional to the belt's inclination to Neptune's orbit plane. With an inclination of only a few degrees, a fraction of an Earth mass in the comet belt could have produced the perturbations attributed to Pluto.

Duncombe *et al.* (1968) have recently determined a new mass for Pluto, finding it to be much smaller than an Earth mass. I hope they will investigate to see whether there is evidence for a comet belt with a pole in the general region indicated in the figure.

So the question is not yet settled whether indeed a comet belt may have produced the perturbations in the motion of Neptune. There is, however, another method of searching for a comet belt; that is by its possible effect on the motions of long-period

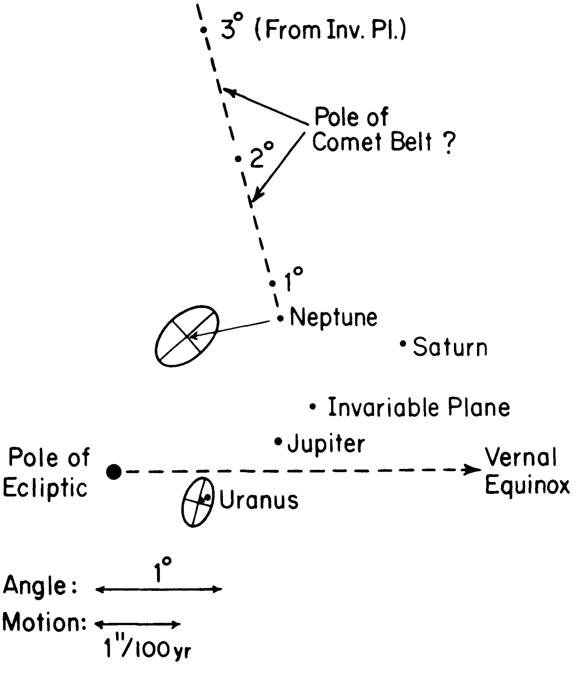

Fig. 6. Pole of ecliptic and possible comet belt.

comets. Halley's Comet, for example (Figure 7), has its aphelion beyond Neptune and not far from Pluto's orbit. Consequently, it would be affected near aphelion by the gravitational attraction of a comet belt in that region of space. There are a few other comets that could be used, but Halley's is the most suitable. So Hamid, Marsden and I have looked into the last two apparitions of P/Halley to see whether there was any evidence for perturbations produced by an assumed comet belt beyond Neptune (Hamid *et al.*, 1968). We were not able to find direct effects in the motion of P/Halley to indicate the presence of a comet belt. But we could set upper limits to the total mass possible in that region of space. If there is the comet belt in a ring at solar distance 50 AU near the invariable plane, we can say with some confidence that its total mass does not exceed the mass of the Earth.

Because we still do not know whether such a comet belt exists, I hope that you will keep its possibility in mind. Perhaps you will find a more ingenious method for either discovering the existence of the comet belt or of proving that its mass is negligible.

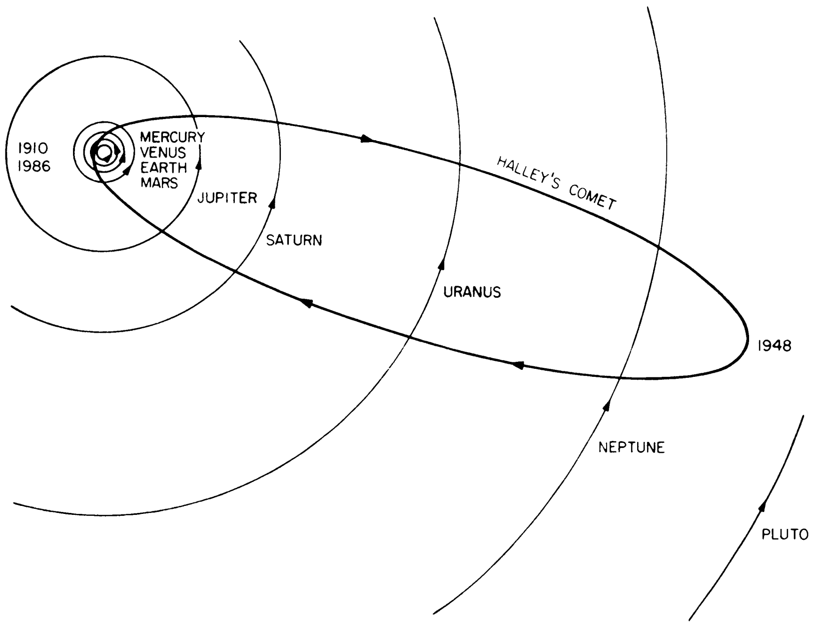

Fig. 7. Orbit of Halley's comet.

References

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Hamid, S. E., Marsden, B. G., and Whipple, F. L.: 1968, *Astron. J.* **73**, 727.
Whipple, F. L.: 1964, *Proc. Natl. Acad. Sci.* **51**, 711.

Discussion

S. K. Vsekhsvyatskij: How do you account for the large mean densities of Jupiter's satellites?

F. L. Whipple: I presume that Jupiter's satellites were formed in the same fashion as were most of the planets (except for Jupiter). The same properties exist in the system as in the solar system itself, namely that the denser bodies are near the primary and the less dense bodies farther away.