THE ASTEROIDAL PLANET AS THE ORIGIN OF COMETS

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ABSTRACT. Recently, M. W. Ovenden has raised seemingly plausible dynamical arguments which suggest that a 90-earth-mass planet existed in the present location of the asteroid belt until 16×10^6 years ago, and then rapidly disintegrated. He mentions supporting evidence from the cosmic ray exposure ages of chondritic meteorites. If the long-period comets originated from the recent disintegration of such a planet, several otherwise improbable characteristics of their orbits would be predicted, including a tendency for those orbits which are least perturbed to return to the site of the original break-up. In this investigation, we compare observed characteristics of long-period comet orbits with expected characteristics, based on the missing planet hypothesis. The conclusion is that long-period comet orbits are wholly consistent with the hypothesis; indeed, certain of their characteristics are difficult to explain in any other way.

OVENDEN'S HYPOTHESIS

Ovenden (1972,1973) has presented seemingly plausible evidence for the existence of a planet of 90 earth masses revolving in the present location of the asteroid belt until 16×10^6 years ago, at which time it rapidly dissipated. In essence, he notes that the solar system is not currently in an equilibrium configuration (the time average of the disturbing function is not a minimum, despite an estimated relaxation time of considerably less than 10^9 years). If Ovenden's calculations are correct, they constitute a proof that the planets have been disturbed in the relatively recent past, and that they may now be seeking a new equilibrium configuration.

Since Ovenden's method leads to a dynamical derivation of the Titius-Bode law, the results themselves suggested the possibility that the disturbance consisted of the disintegration of a former planet in the present location of the asteroid belt. With the aid of the assumptions that the planets were in equilibrium and in orbits close to their present ones before the break-up of the hypothetical planet, he found

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the mass of the planet to have been 90 earth masses; and by invoking the Meffroy (1955) formula for the secular variations in semi-major axis, he estimated the epoch of disintegration at about 16×10^6 years ago. Under these conditions, the present planetary semi-major axes correspond to former equilibrium values to within about one per cent.

The dynamical principles behind Ovenden's arguments seem sound, and are in no way less so even if recent criticism of his time scale proves correct (Ovenden, 1976). He cites additional supportive evidence from the fact that the cosmic ray exposure ages of chondritic meteorites have a sharp cutoff at about 22×10^6 years, whereas, by contrast, some iron meteorites have ages of 10^8 to 10^9 years. This, too, suggests a relatively recent break-up event in the solar system.

BREAK-UP SCENARIO

We have posed the following question: If Ovenden's hypothesis is correct, are there any other observable consequences? It seems clear that there is at present only about 0.001 of an Earth-mass left in the asteroid belt. Therefore, to dissipate the original mass so completely, and to leave no single fragment of significant size, the break-up would seemingly have involved very great energy. Let us assume a normal distribution of post-break-up velocities, with small masses sent out in all directions from the site of the break-up. Since the circular orbital velocity of the hypothetical asteroidal planet would have been about 18 km/s, an additional forward velocity of just 7 km/s would be sufficient for escape from the solar system (since escape velocity at 2.8 AU from the Sun is about 25 km/s); whereas in the opposite direction, a total increment of about 43 km/s relative to the planet is required to reach escape velocity. Despite these asymmetries, if the break-up is sufficiently energetic, most of the mass will escape from the solar system. Masses near the tail end of the velocity distribution curve would continue in direct orbits around the Sun. Between these extremes there will be many masses in a great variety of orbits. Most retrograde orbits and those of high inclination are unstable - these would be drastically altered by planetary perturbations. Almost all would eventually be swept up by the Sun or planets, especially Jupiter, or be ejected from the solar system. A few will find stable orbits, while others might be captured and become planetary satellites. The only salient point here is that it is quite difficult to predict the evolution of the orbits of the surviving objects after about 10^7 years. However a few objects with velocities very close to escape velocity will enter very long-period orbits which will have considerably less mixing with the planets. These we may hope to be able to trace for 10^7 years. Such objects are, of course, observed - the very long-period comets. We will now examine to what extent the known characteristics of such comets are consistent with the Ovenden hypothesis. The accepted division between short- and long-period comets is at a period of 100 years. For present purposes we need to introduce another division - the "very-long-period" comets, with the periods all on the order of 10^6-10^7 years.

VERY-LONG-PERIOD COMETS

Much of our knowledge about characteristics of comet orbits is summarized by Marsden (1974). There is no certain case of any comet having entered the domain of the planets on a hyperbolic trajectory, although something approaching half of the long-period comets leave on hyperbolic trajectories, never to return. They are clearly solar system members before encounter, and therefore could not come from other stars. Yet they come in from all directions on the sky, and their orbit planes have all different orientations.

Any theory attempting to explain the origin of very long-period comets must deal with one striking fact - although they are solar system members, they are apparently approaching the Sun and planets for the first time! One proof of this was recently reviewed by Marsden and Sekanina (1973). There is a tendency for the pre-encounter aphelion distances to cluster near 50,000 astronomical units; whereas there is no such tendency for the post-encounter aphelia. If these long-period comets had passed through a previous perihelion, the clustering of aphelia would have been widely dispersed. Members of this group of first-appearance comets are called "new" comets.

EVOLUTION OF VERY-LONG-PERIOD PLANETOIDS

Let us now examine the evolution of very-long-period planetoids resulting from the break-up up the hypothetical planet, assuming for the moment that the break-up epoch was 16×10^6 years ago. Initially, let us ignore interstellar perturbations. Then those planetoids with aphelia greater than 125,000 au corresponding to a period of 16×10^6 years will not yet have returned, and those with aphelia less than 125,000 AU will have already returned at least once in the past and have had a pseudo-random perturbation of their periods. As a result, about half of these will be given additional energy, resulting in escape. The other half will lose energy, resulting in a second encounter with the solar system after a much shorter time - typically, about 50,000 years. In later encounters these will eventually escape or evolve into short-period planetoids.

Since all of the non-escaping orbits are fixed ellipses until perturbed, they must all originally have had a common intersection point at the site of the original break-up. Moreover, although all periods will be represented by the various orbits, only those ellipses with periods exactly equal to the time since break-up will be returning for the first time at the present epoch. We therefore see that the clustering of aphelion distances of comets within a small range toward all directions on the celestial sphere follows in a natural way from Ovenden's hypothesis.

In order to agree with Ovenden's time scale, the period of these first-return comets must be nearly 16×10^6 years, corresponding to aphelia of about 125,000 AU. The clustering noted by Marsden and Sekanina (1973) peaks at about 60,000 AU. The quantity they determine, 1/a, the reciprocal of the pre-encounter semi-major axis, has a mean value of about 0.000034 ± 0.000007 for the first-return comets. This corresponds to periods of between 4×10^6 and 7×10^6 years, and is therefore somewhat shorter than Ovenden's time scale. Ovenden (1976) has, however, recently criticized his own time scale calculation; and there is clearly no conflict between his results and the above estimate.

SELECTION CRITERIA

In order to further test the connection, if any, that comets may have with Ovenden's hypothetical planet, the next step is to select all of the "new" comets from the Marsden catalog (1975), and to compare the distribution of their orbital elements with the predicted distributions. In order to minimize the number of multi-return comets in the sample, stringent selection criteria were established. If the perihelion distance was less than 0.5 AU, it was assumed that the non-gravitational forces would preclude estimation of the period with sufficient precision. And, the determined values of the reciprocal semi-major axes, 1/a, were corrected to their pre-planetary-encounter values by removing the effects of planetary perturbations, using the method of Everhart and Raghavan (1970). Then only those comets with pre-encounter values of $1/a < +2 \times 10^{-4}$ were kept. After application of these criteria, 60 comets remained in the sample; and these 60 'very-long-period' (VLP) comets were used in the subsequent analysis.

TESTING THE HYPOTHESIS

If these 60 comets originated in the energetic break-up of a planet, certain specific characteristics in the distributions of their elements will result, most of which are unlikely to occur with any other type of origin. A clustering in the periods of first-return comets is one such characteristic. Another is a common point of intersection of all of the orbits at the original epoch. Beyond that there are certain asymmetries in the distributions which should result, even for a symmetric break-up.

Most importantly, we must see the 'Sun-selecting influence' in the distribution of aphelion directions. The Sun-selecting influence results from the fact that the planetoids resulting from a break-up go immediately into a solar orbit; those energetic enough to move in a straight line or other hyperbolic trajectory are of no interest here, because they would escape from the solar system directly. Since the Sun is in a certain specific direction from the point of break-up, the distribution of perihelion and aphelion directions of VLP planetoids will be symmetric about that direction, but will differ markedly in the solar and anti-solar directions. This characteristic is classified as most important because it is the least likely to be altered by either of the two important perturbation sources for VLP comets - passing stars and the galactic field. If VLP comets are connected with the Ovenden hypothesis, the Sun-selecting influence must be present.

SUN-SELECTING INFLUENCE

For spherical symmetry the principal effect of the presence of the Sun is to place approximately 71% of the perihelia in the break-up hemisphere, with only 29% in the opposite one. Including the effect of an original circular velocity for the hypothetical planet changes these percentages to 82% and 18%, respectively.

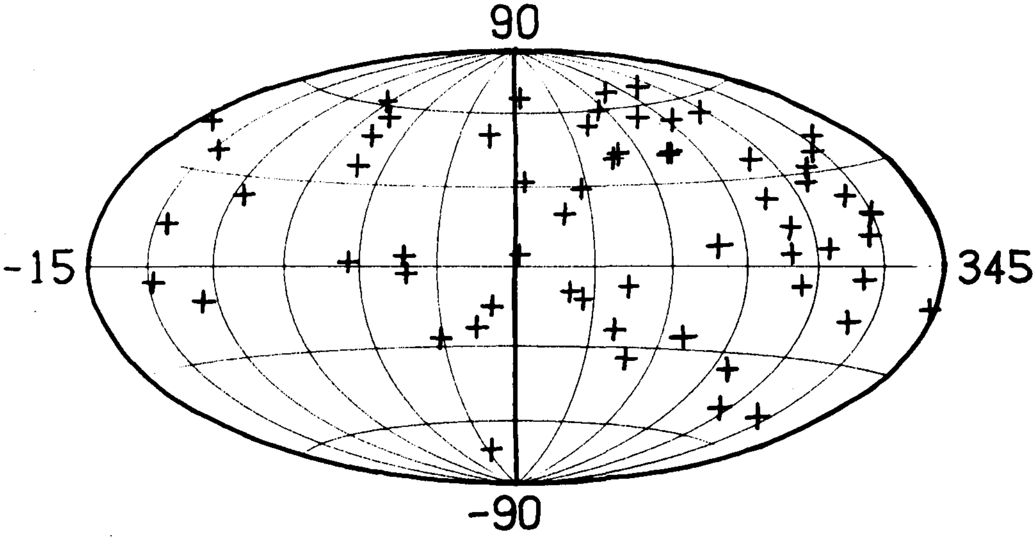

Figure 1. Perihelion directions of 60 VLP comets in ecliptic coordinates centered at longitude 165°, with celestial equator shown.

Figure 1 is a plot of the perihelion directions in ecliptic coordinates for the sample of 60 VLP comets. It is centered on ecliptic longitude 165°. The hemisphere from 165° to 345° contains roughly twice as many perihelia as the opposite one (42 vs. 18, which is 70% vs. 30%). However, observational selection effects have operated to reduce the ratio greatly. It is well known that there are more cometary perihelia observed north of the celestial equator than south, because of the bias in the locations of observatories on the Earth; but the break-up direction (presumably at longitude 255°, latitude 0°) lies well south of the equator. Hence we can discover relatively fewer comets toward the break-up direction, and relatively more toward the opposite direction (which lies well north of the equator). By integrating the distribution function over the northern hemisphere only, and dividing the result into the number of observed perihelia from Figure 1 in each part of the northern hemisphere, we arrive at estimates of the total number of perihelia which would have been observed over the whole sky if there were no selection effects - 145 and 27, which is 84% and 16%. The agreement between prediction and observation is excellent - the cometary perihelia clearly exhibit a strong Sun-selecting influence, as well as the effects of an initial circular orbital velocity around the Sun, and there is negligible probability of such a strong directional bias occurring by chance.

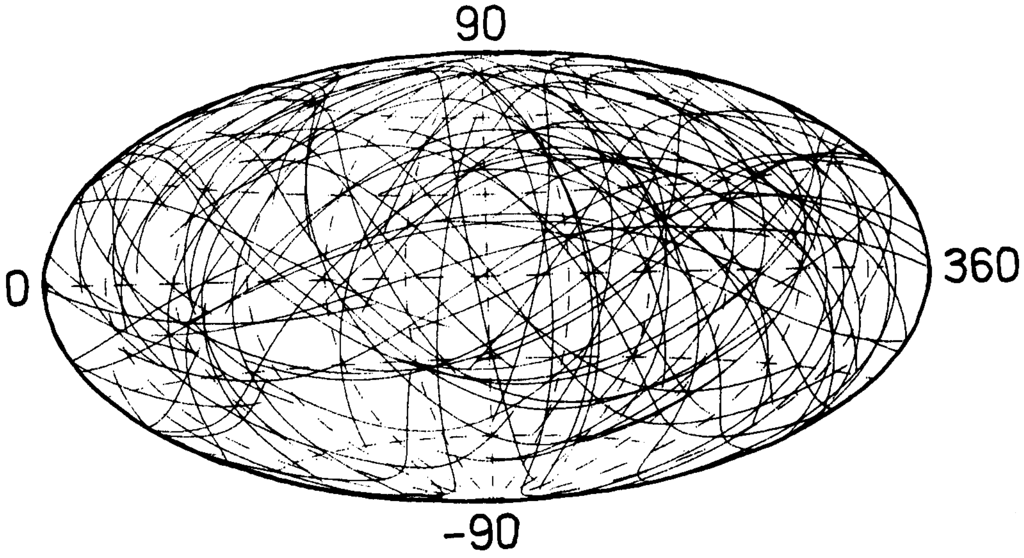

Figure 2. Heliocentric orbit planes for 60 VLP comets at present epoch, in ecliptic coordinates centered at longitude 180°.

DISTRIBUTIONS OF OTHER ELEMENTS

Figure 2 is a plot of the portions of the orbit planes within 30 AU of the Sun, or twice the perihelion distance, whichever is greater, at the present epoch as seen from the Sun. If all of these comets originated simultaneously from a single point, then the initital orbits will all intersect at that point. In Figure 2 there is indeed a statistically significant intersection point at ecliptic longitude 249°, latitude +17°. Since all of these orbits are great circles, there is a second intersection point diametrically opposite on the celestial sphere, at (69°, -17°). The former is a denser clustering only because more comets are near perihelion there. Near the center of this clustering, four orbits with widely different aphelion directions and inclinations intersect within one one-hundredth of a square degree. A second independent clustering at (312°,+20°) is also statistically significant. However, many orbits do not come close to either of these points. If the planetary break-up hypothesis is correct, then perturbations on the orbital planes over some 10^7 years must be able to account for the present dispersion of most of the orbits. Only two possible sources of such perturbations are known - encounters with passing stars, and the tide-like force of the gravitational field of the galaxy.

STELLAR ENCOUNTERS

To those not already familiar with the statistics of stellar encounters, it may come as somewhat of a surprise that stars frequently pass closer to the Sun than the aphelion distances of VLP comets. A study of stars in the solar neighborhood has led to the result that in 5×10^6 years there will probably be half-a-dozen stars passing closer to the Sun than the aphelion distance of a comet with that period, including one encounter perhaps within 25,000 au. Although somewhat disruptive, such close encounters do not 'rip off' the cloud of comets completely because they occur so rapidly. Typically a star will recede to more normal distances again within a few times 10^4 years. Hence the total integrated perturbing impulse to the comets is quite small, except for individual cases of very close approaches. The often-quoted analogy is that such a stellar encounter with the comet cloud is like 'a bullet shot through a swarm of bees'.

The effect of chance encounters with passing stars will be a tendency to randomize the velocities, and hence elements, of the long-period comets. Oort (1950) argued that the randomization must be complete if the process has continued for 3×10^9 years. For a time as short as 5×10^6 years, however, the randomization is far less complete; and we may still expect to discover traces of the original distribution of elements. But we are forced to treat the program statistically.

To order of magnitude accuracy, we can estimate the mean size of stellar perturbations on typical comets. For the orbital plane, the mean perturbation in 5×10^6 years would be ± 2.1 radians. The perihelion direction would be disturbed only ±0.01 radians. For 1/a, we predict $\pm 0.5 \times 10^{-6}$ AU^{-1}; and for q, we estimate a mean error of ± 4.2q. Although these might seem somewhat pessimistic for being able to test the Ovenden hypothesis, we can consider that many comets will be perturbed by much less than these mean amounts, and that in general, the comets we see are selected from among the least perturbed, since their perihelion distances must not have been too greatly altered.

GALACTIC FIELD

The perturbing influence of the galactic field on VLP comets has been investigated by other authors (e.g. Chebotarev, 1966), but primarily for the case of long-term, nearly circular motion at the distance of the 'comet cloud'. Since our VLP comets presumably never had anything like circular motion around the Sun, but instead almost cease moving near their aphelia (typical aphelion velocity for a = 30,000 AU and q=1 AU is 0.3 m/s), the galactic influence is relatively quite a bit larger than it is usually considered to be. At the Sun's distance from the galactic center, 10,000 pc = 2.06×10^9 AU, the galactic field is close to a simple inverse square force field directed toward the galactic center.

Our interest is to numerically integrate the comet orbits backwards to their previous perihelion passage, taking account of the galactic field perturbations. As we increase the adopted period of the comet the perturbations increase from several independent causes - greater exposure time to the perturbations, greater semi-major axes resulting in greater galactic shear, and slower aphelion velocities resulting in less inertial resistance to perturbation. For periods over 10^7 years (a = 46,000 AU), the galactic perturbations are drastic.

As we go backwards in time, the two clusterings near longitude 249° and 312° draw closer together until they finally merge; and at the same time they approach closer to the ecliptic plane - a very important attribute, if the origin point was indeed a planet in the solar system. At 6×10^6 years (Figure 3) the clusterings have essentially merged and are quite close to the ecliptic, and the integration is still fully reversible - i.e. the present configurations (Figure 2) result inevitably from the configurations in Figure 3 after 6×10^6 years of galactic perturbations. The clustering in Figure 3 is obviously quite pronounced; and there is no longer any question of its arising by chance. The degree of scatter of orbits not participating in the clustering is somewhat less than the ±2.1 radians predicted from stellar encounters, as we had reason to hope it would be.

Regarding the orbital inclinations, the initial distribution is close to being proportional to sin i, reflecting random orbit pole locations. At earlier epochs it evolves closer to a flat distribution which is independent of i, as would tend to occur if all of the orbits intersected at one point on the ecliptic. Moreover, an initial bias toward retrograde orbits slowly reverses,and becomes a bias toward direct orbits earlier than 5×10^6 years ago. It is consistent with what might be expected from a normal curve for the initital break-up velocity distribution with a peak at about 26 km/s. The amount of energy involved is comparable with the kinetic energy of rotation of the original planet (assuming Ovenden's characteristics), since rotational velocities on the equators of Jupiter and Saturn are 13 and 10 km/s, respectively.

In connection with the energy of the original event, it may be relevant to note two points here. Although the disappearance of most of the original mass and the absence of a core or single large fragment led us to suspect an event of great energy, ejecting most of the mass from

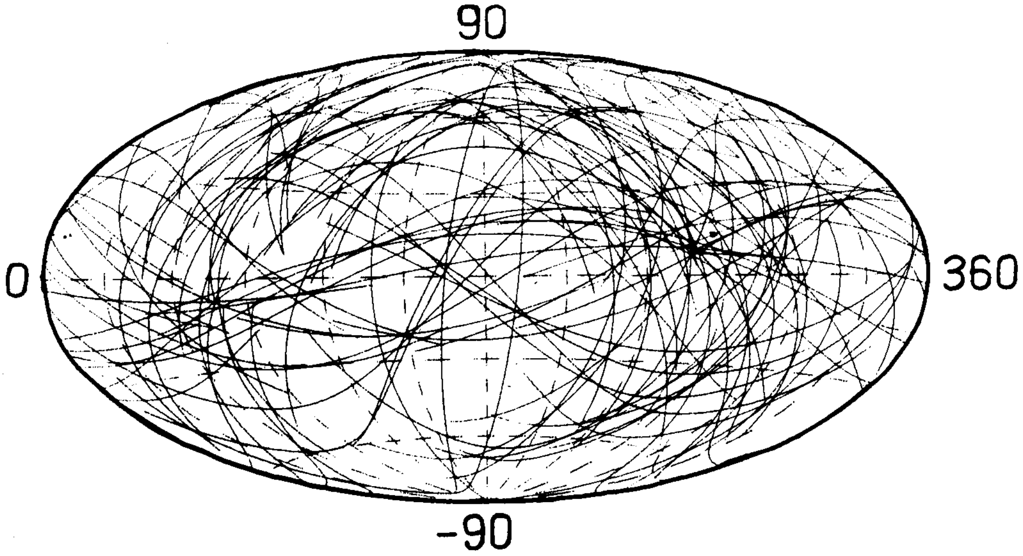

Figure 3. Heliocentric orbital planes for 60 VLP comets 5,800,000 years ago.

the solar system, there are other possibilities. Almost all of the debris from the break-up which is injected into Jupiter-crossing orbits (any part of the orbit exceeding 5 AU from the Sun) will be swept up by Jupiter within about 10^5 years (Wetherill, 1974). This might include a core or substantial fraction of the original mass (See, e.g., Byl and Ovenden, 1975). Also, there are reasons for believing that most of the planet was liquid, which makes it easier to dispose of a great deal of mass without a trace than for a solid planet.

SUMMARY

Ovenden has previously presented dynamical arguments which indicate that a large planet existed in the present location of the asteroid belt until the astronomically-recent past, and than broke up. The cosmic ray exposure ages of chondritic meteorites also argue for a relatively recent break-up event involving asteroidal material. The kinetic energy of rotation alone for such a planet would likely have been sufficient to propel some material with velocities equal to and exceeding escape velocity from the solar system.

In the course of searching for logical consequences of such an event which might lead to a test of Ovenden's conclusions, we have examined long-period comet orbits to determine whether they could have originated in such a way. It has already been shown that short-period comets would have originated from planetary perturbations of long-period comets. We find that the properties of long-period comet elements are completely consistent with the Ovenden hypothesis; indeed many of their characteristics would be difficult to explain in any other way. The Ovenden hypothesis predicts in a natural way the single most remarkable property of long-period comet elements - a clustering in their energy distributions close to the energy of escape from the solar system - a property discovered by Oort, and which could not have survived a single previous perihelion passage. Moreover the cometary perihelion directions show a strong 'Sun-selecting influence' - a property almost immune to perturbations, which is most unlikely to have resulted from any other proposed type of cometary origin.

A break-up type of origin demands that, to the extent that the orbits are unperturbed, they must all pass through the point of break-up upon return to the vicinity of the planets. Such a property is observed; and the clustering of orbital planes, which lies close to the ecliptic plane, increases in intensity as the galactic perturbation effects are taken out of the element distributions. The degree and kind of scatter in the elements at an epoch of $6\text{x}10^6$ years ago is consistent with that expectable from encounters with other stars in the solar neighborhood. This model for cometary origin is also highly successful at predicting some statistical properties of the orbital element distributions, including some not previously known. The epoch of the break-up event can be bounded in several ways, and must lie close to $(6\pm1.5)\text{x}10^6$ years ago.

In short, there are now several independent arguments for the validity of the Ovenden hypothesis, and for a common origin of comets and asteroids from the break-up of a former massive planet of the solar system. As remarkable as this hypothesis is, it would require no major contortion of existing knowledge and theories to accept, but for the single fact that the event is datable to an epoch so recent that primates already walked the Earth!

BIBLIOGRAPHY

Byl, J. and Ovenden, M. W. 1975, 'On the Satellite Capture Problem'. *Monthly Notices Roy. Astron. Soc.* 173, 579-584.

Chebotarev, G. A.: 1966, 'Cometary Motion in the Outer Solar System', *Soviet Astron. - AJ* 10, 341-344.

Everhart, E. and Raghaven, N.: 1970, 'Changes in Total Energy for 392 Long-Period Comets, 1800-1970', *Astron. J.* 75, 225-272.

Marsden, B. G. and Sekanina, Z.: 1973, 'On the Distribution of 'Original" Orbits of Comets of Large Perihelion Distance', *Astron. J.* 78, 1118-1124.

Marsden, B. G.: 1974, 'Comets', *Ann. Rev. Astron. Astrophys.* 12, 1-12.

Marsden, B. G.: 1975, *Catalogue of Cometary Orbits*, Smithsonian Astrophysical Observatory, Cambridge, pp. 1-83.

Meffroy, J.: 1955, 'Contribution à l'étude de la stabilité du système solaire', *Bull. Astron.*, Ser. 2, 19, 1-224.

Oort, J. H.: 1950, 'The Structure of the Cloud of Comets Surrounding the Solar System, and a Hypothesis Concerning its Origin', *Bull. Astron. Inst. Neth.* 11, 91-110.

Ovenden, M. W.: (1972), 'Bode's Law and the Missing Planet', *Nature* 239, 508-509.

Ovenden, M. W.: 1973, 'Planetary Distances and the Missing Planet', *Recent Advances in Dynamical Astronomy* ed. by B. D. Tapley and V. Szebehely), Reidel, Dordrecht, Holland, 319-332.

Ovenden, M. W.: 1976, 'The Principle of Least Interaction Action' (In process).

Sekanina, Z.: 1968, 'On the Perturbations of Comets by Nearby Stars' *Bull. Astron. Inst. Czech.* 19, 291-301.

Wetherill, G. W.: 1974, 'Solar System Sources of Meteorites and Large Meteoroids', *Ann. Rev. Earth Planet. Sci.* 2, 303-331.