50. METEOR DYNAMICS

(Round-Table Discussion and Summary)

Chairman: F. L. Whipple
(Smithsonian Astrophysical Observatory, Cambridge, Mass., U.S.A.)

Whipple: It is quite impossible for me to make a proper summary of the many major contributions on meteors presented at this most exciting symposium, and I shall make no attempt to do so. I can better point out trends and possible goals. First a reminiscence. It is more than 30 years ago when I first began seriously to study the problems of meteors. A major expectation then concerned hyperbolic meteor orbits, or meteoroids originating in interstellar space. We knew, of course, that many meteors came from comets and supposed that some of the sporadic meteors came from asteroids. These problems appear now to be largely solved, although the negative results with regard to hyperbolic meteors are definitive only at the 1 % level. With our more precise instrumentation and continued observations I would not be too surprised if we might someday find an interstellar meteor. The expectation might be as high as 10^{-4} among observed meteors. The contribution of the asteroid belt, particularly carbonaceous chondrites or whatever similar fragile bodies are indicated by McCrosky's observations of the fireballs, is truly uncertain. Both Ceplecha and Kresák have shown some strong evidence that we cannot discount possible asteroidal contributions among the photographic meteors.

The numerous papers on meteor streams, particularly in the radar area but also in the optical region, indicate clearly that it is vital to agree internationally upon definitions for meteor streams. I believe that the Commission 22 of the IAU should take this responsibility. If not, we will find continuous conflict among the observers and theoretical groups over questions which are largely matters of definition. Once these definitions have been agreed upon, the theoretical interpretation then can follow the more classical procedures of science, at least to the extent of giving the uninformed reader some clear concept of the nature of the discrepancies, whether they be observational or theoretical.

The modern amazingly rapid computing machines are revolutionizing our approach to many meteoritic problems. I do hope that the opportunity for such rapid calculations does not deter our investigators from proper theoretical developments. In many respects the computing machine is like a beautiful woman. A man can become so enamoured that he bestows on her all his time, his energy and his fortune. To carry on this simile, the ideal solution is perhaps more like our modern concept of marriage:

Kresák and Millman (eds.), Physics and Dynamics of Meteors, 518–525. © *I.A.U.*

theory and computation should carry jointly the responsibilities for team success.

The discovery of carbon compounds in a fireball spectrum by Ceplecha is of great significance. I wait with great interest to learn the extent that this observation indicates a cometary origin for the fireballs or whether we should expect a similar spectrum from a meteorite such as a carbonaceous chondrite. It is clear that the fireball observations are highly significant in determining the relative contributions of asteroids and comets to the meteoritic complex. It is clear also that improved theory of ablation, luminous efficiency, and electron production mechanisms for all-sized meteoric bodies is critical to immediate progress in meteor studies. The physical theory can certainly be improved by careful attention to the important observations by Babadžanov with such a short time-scale resolution of meteoric phenomena.

I was quite surprised to find that the observations of the Leonids were so exciting. These observations have the potential of giving us enormous new insight with regard to the production and development mechanisms of meteoric streams in space. The theory remains surprisingly unsatisfactory in predicting the observational characteristics of streams. It deserves much more attention. I hope that the theoreticians will follow closely the observational progress made in both recent and future Leonid studies. It seems to me inevitable that non-gravitational effects play a significant role in the dispersal of meteoroids in streams. To my knowledge we have almost no theory involving such forces and their effects normal to gravitational orbits. The many fine measures of the mass indices of meteors, both sporadic and shower, are, I think, vital clues in these theoretical determinations. Dohnanyi's contribution is also of great significance. I wish to congratulate him on his fine discussion of collisional interactions among the asteroidal bodies. My own studies in this direction for the smaller particles are still very crude and I have made no effort to determine what effect collisions may have on the orbital characteristic of the remaining particles.

With regard to streams, I note that not all meteor streams are *necessarily* cometary. Possibly an Apollo asteroid of carbonaceous chondritic composition might produce a meteor stream by collisional spallation. A search for meteor streams associated with Apollo asteroids might be fruitful; or even conversely?

A great puzzle still confronts us regarding the impact rates of meteoritic dust on the space vehicles and the collection rates both in the Earth's atmosphere and in near-Earth space. The forthcoming COSPAR symposium on this subject should be clarifying. I regretfully ignored this huge mass of information in discussing the nature of the Zodiacal Cloud. Again we await final conclusions, both theoretical and observational, regarding the Zodiacal Light itself, in order to ascertain whether micron-size particles and smaller are the major factors in producing the Zodiacal Light, or whether it can be produced by larger particles of coarse structure.

We have a serious problem in establishing the detectability of high-velocity and high-altitude radar meteors. I am not convinced that we have yet obtained a clear estimate of the unobserved meteor passages in this category. It is very important that optical observations be coupled with radar observations for these fainter high-altitude objects. Radar velocity measures here might also be of importance.

Southworth: I do not know of any Doppler measures in the initial part (Fresnel pattern) of meteor echoes.

Kaiser: The physical nature of the meteoroids is likely to be reflected in the initial structure of the ionized train. The most sensitive way of studying this by radar may be through phase measurements such as those pioneered by Greenhow. A difficulty is the separation of phase variations arising from the initial expansion of the train from those due to winds and other causes. We may perhaps resolve the problem by multiple wavelength phase measurements and at the same time understand better the radar-reflection processes.

Whipple: We should continuously keep in mind the possibility of observing meteor streams outside the atmosphere. Already there is evidence for such streams from the deep-space probes by both the U.S.A. and the U.S.S.R. It is possible that streams might be seen in scattered light at night, particularly by space vehicles above the atmosphere. Also, it is possible that we could see them from the ground by looking along the direction tangential to the stream orbit. Dr. B. Marsden is now making calculations for the Zodiacal Light observers. I should welcome any comments with regard to problems of meteor streams.

Levin: It remains unexplained why meteor streams of great width have a concentration of large particles towards the core of the stream. Such a concentration is natural in a young filamentary stream, where it is due to the smaller velocities of large particles relative to the nucleus of the parent comet. But, if we explain the great width of meteor streams as due to planetary perturbations, such a concentration should have disappeared. However, the observations show that it does exist, and one must look for the explanation.

Whipple: I hope that more effort will be made by theoreticians to solve the many problems of electromagnetic effects on small meteoroids in space. The charge on meteoroids in space can amount to at most a few volts but the interaction with the magnetic fields of the solar wind have not been explored thoroughly, nor has any serious attempt been made to evaluate the rotational effects that can be introduced on small particles in space by collisions. Such effects may greatly influence the lifetimes of particles in space and also the dispersions within streams.

A major problem of origin concerns the faint 'toroidal' radio meteors. Personally I have been attracted only to two possibilities: (a) the toroidal meteors derive from one or a few large comets in such orbits, or (b) particles in such small highly inclined orbits spend a smaller fraction of their time in the dense Zodiacal Cloud than average particles and consequently survive longer because of smaller erosion rates and fewer destructive collisions.

Southworth: Conceivably the toroidal group could be connected with the Jupiter barrier problem. Some orbits severely perturbed by Jupiter when their aphelia were near Jupiter's orbit could be thrown into the relatively stable toroidal group and persist there much longer than orbits of lower inclination persist.

Bronšten: I want to describe here an old hypothesis about the origin of the asteroidal belt. This hypothesis was put forward by the late Professor K.N. Savčenko in 1957 at the Odessa meteoric conference, but the death of Professor Savčenko prevented its publication. This hypothesis is very interesting but could be considered as somewhat fantastic.

The summary of this hypothesis is as follows: Between the orbits of Mars and Jupiter there existed a great planet (Phaeton) with five satellites: Ceres, Pallas, Juno, Vesta and a fifth, the outermost satellite, that was near the limit of Hill's stability surface. The perturbations from Jupiter led this satellite out of Hill's sphere and for many million years it was an independent planet. But after many revolutions around the Sun this body entered again into the Hill's sphere of Phaeton, but in such a way that it impacted with the planet and broke it up into many small fragments, forming the present asteroidal belt.

In connection with this model we can also examine the system of the irregular

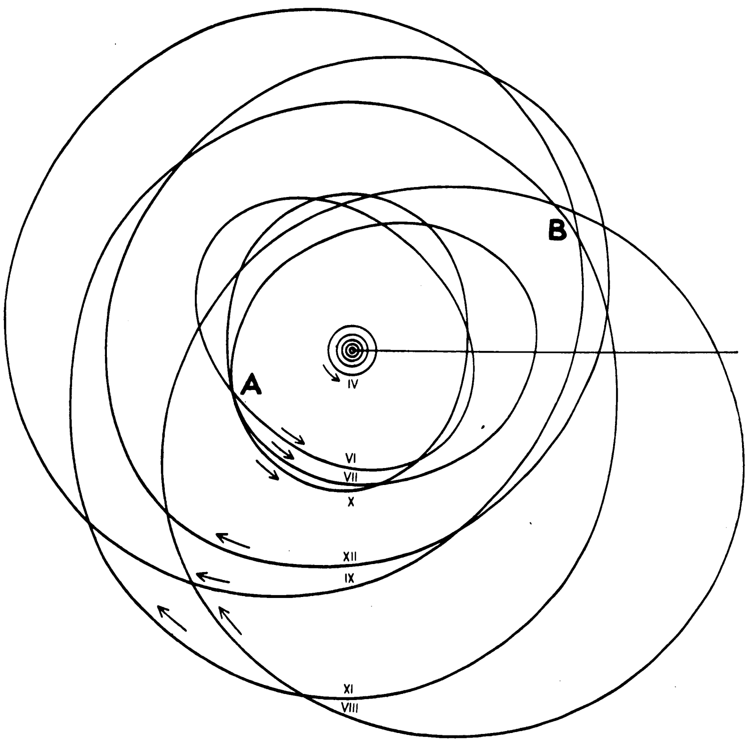

FIG. 1. *Orbits of Jupiter's satellites. A – point of the intersection of three inner irregular orbits (VI, VII, X), B – region of the close approach of four outer irregular orbits.*

satellites of Jupiter. There are two groups of these satellites: three satellites at the distance of about 11 million km from the planet, their orbits having a common point, and four situated in the range of 21–25 million km from Jupiter. The orbits of these four satellites have no common point, but a region of close approach. It should be noted that the orbits of these satellites are situated outside the sphere of stability (Hirayama). My opinion is that each group of irregular satellites of Jupiter has been formed as a result of the impact of an asteroid with a regular satellite of this planet. One can calculate that the velocity of approach of such an asteroid, having a perihelion distance about 1 AU, would be 6 km/sec. That is the upper limit of the approach velocity. On the other hand, the physics of hypervelocity impact enables us to approximate both limits of this velocity on the basis of the assumption of the fragmentation of the satellite into 3–4 pieces, without an explosion.

All aspects of this hypothesis must be verified by corresponding calculations.

Kresák: I think that the perturbations of the orbits of Jupiter's outer satellites are so strong that there cannot be any common point which is permanent.

Whipple: With regard to the asteroids, including the Apollo group, the uncertainties in mass are shockingly large. Our entire information comes from magnitude measures coupled with completely hypothetical albedo assumptions. Since the masses vary as (albedo)$^{-3/2}$ the uncertainties in mass are extremely great, perhaps 30 times, and enter as a major factor in the problem of the cometary vs. asteroidal origin for the Apollo group. Any success in measuring their diameters by space probes or radar would add enormously to our confidence in solving the asteroidal vs. cometary origin problem. The uncertainty in density still remains but need not be as great as a factor of 2 in mass.

Lindblad: What is the present situation and planning as to a space probe to the asteroidal belt? Such a probe could solve several important problems of asteroid research.

Dohnanyi: There are study programs at NASA for manned missions that would have orbits with aphelia at 2·2 AU; such a mission may be suitable for resolving the angular size of some of the asteroids. There are furthermore several study programs at NASA for unmanned craft to fly into or through the asteroidal belt.

Whipple: The uncertainty in mass for asteroids greatly affects the solution of Dohnanyi's problem when one applies numerical values. All of the recent meteoritical work from laboratory chemistry indicates that the iron meteorites were not formed in huge asteroids of lunar size but most probably in very much smaller asteroids comparable to the intermediate or larger ones now observed in the asteroid belt. Thus the older concept that the asteroids were formed originally as a few minor planets of perhaps lunar dimensions, now broken up by collisions, seems less and less likely. It is quite possible that shortly after the primeval gas had been blown out of the system, the asteroid belt may have appeared much as it does today. If the break-up rate for asteroids is relatively slow, it is quite possible that we have relatively small ones that are still preserved, particularly in the inner portion of the belt around Mars where collisions are less serious. These, of course, could provide us with friable asteroidal material. We seriously need more thorough calculations of perturbations for asteroidal objects as well as for comets and meteor streams.

Levin: I hope that the calculations of perturbations of different meteor streams, similar to those reported yesterday for Leonids, will be continued at the Institute of Theoretical Astronomy in Leningrad.

Fedynskij: I would like to call your attention to the fact that the investigations of perturbed motion of such showers as the Leonids and the Cyclids lead us to conclusions about the relative stability of some showers. This is supported also by a comparison of the positions of the large meteor showers obtained from ancient China, and from the modern observations by Astapovič and Terenteva. This is important, because several years ago it seemed that the lifetime of meteor showers should be relatively short, perhaps several hundred years only.

Whipple: It is clear that the ancient observations of meteor streams as reported by Fedynskij for his colleagues will play an increasingly important role in our understanding the development of meteor streams. We need particularly to investigate the effects of strong local perturbations of these streams at the times of their close approaches to the planets.

Fedynskij: Yes, I agree, there are indeed strong perturbations of small parts of meteor streams.

Lancaster Brown: Would you care to discuss at length Öpik's idea that the Apollo-group asteroids were formerly nuclei of the Comet Encke type?

Whipple: I have attempted to find data or theories that would give a clue as to the origin of the Apollo asteroids, whether they are old comet nuclei as persistently upheld by Öpik, or whether they are truly asteroids. Öpik's rather remarkable theory for the possible origin of the Apollo asteroids by perturbations from Mars-crossing orbits fits the data fairly well. Within an order of magnitude it predicts the observable number of Apollo asteroids. First there is some uncertainty in this number, which I conclude cannot be less than about 50 and perhaps may be very much greater.

Öpik has shown that for typical orbits crossing that of the Earth the mean lifetime is $\sim 10^8$ yr, and for Mars $\sim 6 \times 10^9$ yr. Hence, the number of primitive asteroids crossing the orbit of Mars has been reduced by a factor of e, while those crossing the orbit of the Earth have been reduced to $\sim e^{-46}$. To maintain the Apollo group crossing the Earth, about 300 times as many must cross the orbit of Mars at the present time. The difficulty arises from the fact that we cannot observe as small asteroids at the distance of Mars as the Apollo group crossing the Earth's orbit. Thus we must extrapolate over several magnitudes from the faintest asteroids seen crossing Mars' orbit. Perhaps from Dohnanyi's work one can establish a value for the distribution function with mass but without it one finds considerable uncertainty. It is quite easy to fit Öpik's theory to the observed number of Apollo asteroids by simply assuming a larger value for the mass index than Öpik had assumed. There is, however, another limit set at a slightly larger asteroidal size by Baade's observations of faint asteroids. Here, of course, we do not know the distance of the faint asteroids that he observed photographically. If we assume that they are distributed with semi-major axis as are the larger asteroids, there are not enough to produce the Apollo asteroids. On the other hand, if Baade's faint asteroids are largely concentrated in Mars-crossing orbits, the observed number would be quite adequate to provide a continuous supply of Apollo asteroids by Mars perturbations.

In addition there is another problem. What do we mean exactly by Mars-crossing orbits? The eccentricity of Mars' orbit changes over quite a large range and consequently aphelion distance changes appreciably. Thus a factor of 2–4 uncertainty exists in the number of asteroids whose orbits, taken statistically over long periods of time, really qualify as Mars-crossing.

Furthermore, we still have no knowledge concerning the rate of dissipation of extremely old cometary nuclei such as that of Comet Encke. I hope that data can be obtained to clarify this problem. Dr. S. Hamid and I are seeking possible identifications of Comet Encke among the ancient comets observed by the Chinese. If such identifications exist we will then have a measure of the brightness decrease for a comet that has contributed significantly to the zodiacal cloud. Note, too, that the dissipation rate for a new comet is perhaps 10^9 times that for a stony asteroid. Even though a comet nucleus is fairly inactive its rate of break-up may still be far more rapid than that of a typical asteroid, even a 'half-baked' one. On the other hand, the largest comet nuclei may be huge. We really do not have reliable limits; 60–100 km radii??

In view of all these uncertainties I feel at the moment that the odds are perhaps two or three to one in favor of the Apollo asteroids being mostly old cometary nuclei. This means really that I consider the problem unsolved.

Dohnanyi: My calculations imply that relatively few asteroids in the asteroidal belt have escaped catastrophic collisions during the life of the solar system.

Whipple: There is always a possibility that stable resonances also affect the interaction of Mars with asteroids in orbit near it. The motions of the lines of apsides complicate the problem.

Kresák: Due to the alignment of the lines of apsides of the asteroids with that of Jupiter, the ratio of the spatial densities of the asteroids at the same heliocentric distance, $r = 1{\cdot}5$ to $1{\cdot}8$, but in two opposite directions from the Sun, is as large as 10:1. Space missions into this zone, even with equipment recording no more than the number of impacts, would be very useful for discriminating between the cometary and asteroidal particles since the cometary particles should show no analogous asymmetry in their longitude distribution.

Guth: I point out the importance of resonance, which could play a substantial role in the stability problems of the orbits of comets and of meteor streams connected with them (e.g. Comet Pons-Winnecke with the ratio of daily motion to Jupiter 2:1).

Whipple: It is clear that this most important symposium on meteor dynamics has added enormously to our understanding of some problems. It also has added to the number of problems that appear within range of solution. I know you will all join me in expressing our profound appreciation and gratitude to Dr. Kresák and Dr. Millman for planning this Symposium and to Dr. Kresák, his staff, and the other Czechoslovakian astronomers who have made possible such a beautifully organized symposium in such a beautiful area of our planet.