PART X
CONCLUSION

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COMETS, ASTEROIDS AND METEORITES:

UNSOLVED PROBLEMS ABOUT THEIR RELATIONSHIPS, EVOLUTION AND ORIGIN.

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A few of the questions proposed earlier to the contributors are reviewed to identify some of the unsolved problems related to the different interfaces between comets, asteroids, and meteorites and their evolution and origin.

Fourteen years have passed since Middlehurst and Kuiper's book on "The Moon, Meteorites and Comets" (Univ. of Chicago Press 1963). Since then, the study of the Nature of Asteroids has come of age in Gehrels "Physical Studies of Minor Planets (NASA-SP-267, Washington, D.C. 1971) and, because of the success of space exploration, the study of the Moon has become a separate discipline.

For the first time, we have tried here to confront the interrelations between all the minor bodies of the solar system. Of necessity, this book remains incomplete. First, the moon and other *large* satellites had of course been excluded from our considerations, but we have not said much about the smaller satellites either. Second, the interrelations were not always apparent, and have become somewhat tenuous in some of the chapters. However, they can always be felt if the leading thread is not forgotten: the convergence of the empirical data stems from their common origin; we are probably detecting clues everywhere about the origin of the solar system, but we still have a long way to go to understand the whole message.

Since it is an impossible task to be exhaustive and unbiased, the present writer will submit here his incomplete and personal perception of the present status of the questions he had proposed in February 1976, to the contributors.

The authors' names quoted hereafter are all from this book; page references can therefore be found through the authors' index.

INTERFACE BETWEEN COMETS AND INTERSTELLAR MOLECULES

All stable molecules observed in comets have been observed in interstellar space, and all radicals and ions observed in comets could be made by dissociation or ionization of the molecules observed in interstellar space. The correlation is so striking that it must mean something, even if we do not yet understand the message. Is there a similarity in the different processes that make comets and interstellar molecules, or are the processes identical because there is a common origin? Are comets made of interstellar grains dragged along during the

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collapse of the solar nebula, or were interstellar grains ejected during the formation stages of many planetary systems?

In particular, the cometary nucleus seems to contain (Shimizu, Delsemme) much less hydrogen and somewhat less carbon than expected from the simple-minded condensation of the solar nebula at thermodynamic equilibrium, but it could look very much like Greenberg's cold accretion model of interstellar dust. The narrow conditions of Delsemme and Rud's solar nebula model are unattractive: the authors suggest to look towards the clumping of interstellar grains. Whipple's conjecture that the outer layers of the cometary nucleus have been chemically modified by the cumulative cosmic ray damage of the last five billion years must be seriously considered in all its consequences, although it is unclear whether the HCNO content of the interstellar grains will be drastically changed. Dobrovolsky and Kajmakov's simulation of cometary nuclei in the laboratory should certainly be encouraged and Whipple's conjecture could be explored by proton bombardment of snows, but we do not know enough yet to simulate true interstellar grains in the laboratory.

We must also seriously examine whether we have not been fooled by the present charge-exchange chemistry of the inner coma of comets, into believing that it took place some five billion years earlier, in interstellar space. Since we do not have *direct* knowledge of the parent molecules present in the nucleus, Huebner's approach is very relevant, although so far it has not been shown that HCN and CH_3CN could be abundant by-products of the coma reactions. Finally, the clues listed by Donn on the aging of comets, show that much caution is required to distinguish their original composition from their aging properties.

INTERFACE BETWEEN METEOROIDS, AND COMETS OR ASTEROIDS

The cometary origin of many low-density small meteoroids is well established, (in particular from meteor streams, McIntosh), and their identification with chondritic-type material (probably C I, Millman) is rather convincing, helping the analogy between C I chondrites and the non-volatile fraction of comets (Yavnel'). This is confirmed by the chondritic nature of small particles collected in the upper atmosphere (Brownlee *et al.*) and assumed to come from the disintegration of short-period comets. It is also clear that many meteoroids do *not* come from comets; a proposed classification (Ceplecha) which implies several types of asteroidal as well as of cometary materials, should be developed and discussed.

However, many problems remain: Can the largest meteoroids that could reasonably be stripped away by the outgassing of comets be identified with those large fireballs that terminate their trajectory at very high altitudes? Or do they come from the decay of cometary nuclei into large chunks by unspecified mechanisms? Can different density classes be reasonably associated with different orbital characteristics? Can the low crushing strength of some meteoroids be sufficiently quantitatively established, to be used in models for the cometary nucleus? Can the meteor orbits be determined and their early evolution reconstructed with enough accuracy to identify parent bodies? What is the dividing line between orbital properties of comets and asteroids? Can the orbital scatter within meteor streams be readily explained by the ejection velocities from a parent comet (see Sekanina's approach)?

INTERFACE BETWEEN THE ORBITAL EVOLUTION OF COMETS AND OF ASTEROIDS

The dynamical lifetime of planet-crossing orbits is short (Wetherill). Therefore short-period comets as well as Apollo or Amor-type asteroids disappear fast, and a constant supply of both classes of objects is needed to maintain the steady state (Wetherill, Scholl and Froeschle, Everhart, Rickman and Vaghi). The evolution of the cometary orbits can be used for more exotic purposes, like that of making satellites (Singer) or, changing the direction of the

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generally accepted evolution (Vsekhsvyatsky) by feeding Oort's cloud from the source of comets assumedly present within or in the vicinity of the giant planets. These ideas do not seem to gain much acceptance.

The conjecture that the evolution of comets is linked with that of asteroids (Levin), because of the Apollo or Amor asteroids could be dead cometary nuclei, has not received a final answer. The recent search for planet-crossing asteroids (Shoemaker and Helin) suggest that they could be numerous and derive all from dead comets, whereas Kresak estimates from orbital criteria that their majority is of asteroidal nature. The problem of comparing the activity's lifetime of short-period comets, to the dynamical lifetime of their orbit is complicated by the possibility of many scenarios (insulating crust covering an inactive icy body, total disappearance of comets into meteoritic dust, etc.). After the decay of the short-period comet in a few millenia, could mechanical or physical processes make its orbit drift towards shorter aphelia with characteristic times considerably longer (millions of years)? Is there any correlation between the physical properties of asteroids that could be candidates for old cometary nuclei? What is the fraction of cometary nuclei that stop decaying when they have lost their gases?

INTERFACE BETWEEN COMETS AND METEORITES

The present writer has concluded elsewhere that comets are more pristine than even C I chondrites. But his data are scanty, and the dust-to-gas ratio in comets (needed to establish the HCNO-to-metal ratio) remains uncertain by at least a factor of 2; his extrapolation of production rates to nuclear composition is based on the shaky assumption that a steady-state is (sometimes) reached. More and better analyses of the Finson-Probstein type are clearly needed to translate tail isophotes into HCNO-to-metal ratios. A needed confirmation is also the absence of a large fraction of carbon grains in the tails. Many questions remain open: even if "new" comets are pristine, their physical evolution could imply the compaction of a crust, or of a core, that could become very similar to C I chondrites (see in Delsemme, the dust-to-gas ratio of comet Arend-Roland before and during an outburst). Could uncompacted cometary material reach the ground undestructed? Most likely not: this could explain the absence in our museums, of a hypothetical C-zero chondrite class that could be identified to "new" comets, whereas the C I chondrites would correspond (among other possibilities) to the outgassed and compacted core of a (dying) short-period comet, like Comet Encke.

INTERFACE BETWEEN ASTEROIDS AND METEORITES

Spectrophotometric, polarimetric or infrared data for several hundred asteroids have recently brought about a wealth of information: first, the existence of several groups somewhat clustered in their properties has been established; second, their identification into compositional types has been clarified by laboratory measurements of the optical properties of meteorites; finally, the fruitful distinction between primitive and differentiated meteorites has been extended to asteroids, giving some insight on the fragmentation processes. Differences in space distribution of compositional types suggest broad correlations for meteorite sources within the asteroid belt. However, broad advances also bring new questions and new puzzles. For instance, is Al^{26} (Sonett and Herbert) the energy source that has differentiated Vesta, enough to produce its basaltic (achondritic) surface, but has not differentiated Ceres, which is 5 times more massive? Scott resolves 12 groups of iron meteorites, plus some 67 irons that do not fit into one of these groups, which implies at least two, possibly three scores of parent bodies. Could some of them be identified with actual asteroids? Of course, spectral interpretations are not

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yet quantitative enough, and some asteroids may be too small to be seen, or may have disappeared a long time ago. What is the nature of the Trojan asteroids, which put them into a separate physical class? Can they be connected to any meteoritic type?

ORIGIN OF COMETS AND ASTEROIDS

It seems that the present-day asteroids are the remnants of a much larger early population (Chapman). What is the secular stability and the lifetime of early planetesimal rings at different distances around the sun? Can the constraints deduced from the intense early cratering on the Moon, Mercury and Mars be really used to choose among possible scenarios? What is the collisional fragmentation history of a typical asteroid during its life?

The actual existence of Oort's cloud of comets is generally accepted, but its origin is still obscure (Delsemme). Did comets originate, with carbonaceous chondrites, in a primeval belt between Jupiter and Neptune; or beyond according to Cameron's scenario? The hypotheses that imply that some form *in situ* (for instance by some mechanism of the solar wind) do not seem to gain much acceptance. Can new numerical experiments on orbital diffusion shed some light on the origin of Oort's cloud (Everhart)?

What about the few people who want to reverse the direction of the general evolution of cometary orbits? The arrow of time can be deduced from statistical data showing the direction of an entropy increase; can it be done with the distribution of orbital energies among a large set of comets? Is the statistical evidence shown by Delsemme, large enough to conclude against Vsekhsvyatsky's ideas?

ORIGIN WITHIN THE SOLAR NEBULA

The several isotopic anomalies all discovered or confirmed rather recently in primitive meteorites seem concentrated in grains. Their interpretation in terms of pre-solar heterogeneities in the solar nebula (R. Clayton) has brought about a new excitement in a fascinating field. The alternate hypothesis of inducing these anomalies by solar proton irradiation, seems now less attractive (D. Clayton). The extinct radioactivity of ^{26}Al in the Allende grains was apparently large enough at one time to melt kilometer-size bodies! (Papanastassiou, Lee and Wasserburg). Pellas and Storzer's cooling rates constrain the sizes of chondritic asteroids (that obviously did not reach melting point) to a radius of 120 to 200 km. Does it mean that the ^{26}Al distribution was extremely heterogeneous, or that the accretion of minor bodies started late, or at different times, or went on for durations large enough to cool off ^{26}Al into ^{26}Mg before reaching final sizes? Does it contradict the sharp isochronism for the solidification of ordinary chondrites between 4.54 and 4.69 billion years ago?

Could *all* isotopic anomalies *and* extinct radioactivities be explained by *one* single supernova event, triggering the collapse of the Solar Nebula? Was the accretion of the minor bodies really quick enough, to emprison short-lived radioactivities in their grains? What becomes of the time interval previously required to cool off *some* of the early radioactivities? New scenarios will certainly be explored and all consequences are difficult to assess at this time.

Chondrule formation also remains an open problem. Wood and McSween advocate the formation of these "fiery rain drops" at those places where the gas/dust ratio was enhanced in the solar nebula and through transient high-energy events, but many hypotheses still compete to explain these events. Chondritic inclusions (Wilkening, Bild) imply a history of complex interactions which is not always related to the early nebula. Lipschutz and Ikramuddin remark that trace elements in chondrites provide clues to metamorphic losses.

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Recent solar abundance data (Holweger) confirm their increasingly better fit with C I chondrites, for all atoms heavier than oxygen, whereas some probable depletions in HCNO are reported by Delsemme from scanty cometary data.

The mineralogy and chemistry of most chondrites, achondrites, and irons still suggest that they formed in a range of fairly oxidizing conditions, such as in a solar gas between 500° and 360°K. Some classes of irons seem to have formed under more reducing conditions (*i.e.*, higher temperatures). Finally, two rare classes of stones (enstatite chondrites and achondrites) suggest conditions more extreme than could be attained in a solar gas at any reasonable temperature; they seem to require a fractionated gas of $C/O > 0.9$, or a pressure at least as large as 1 atmosphere. Was the carbon-rich domain, needed to explain the enstatite chondrites, obtained by the natural fractionation of the solar nebula, or were special mechanisms required (as induced by the gravitational field of a planet, Williams)?

Can the hydrogen depletion suggested by Uranus, Neptune and the comets, be traced back to a fractionation of the Solar Nebula? How would the presence of interstellar grains in the solar nebula (that could imply a two-phase system as soon as the pressure is large enough) interfere with the chemistry suggested by the meteorites? What was the temperature gradients of the nebula? Where in the nebula would the grains loose their icy mantles, where would they be totally vaporized? Are the density variation of the planets merely a function of nebular temperature, or must other processes be invoked (Williams)?

This type of questioning leads quickly to the consideration of models of the nebula and of the protoplanets, which are outside the scope of this book. This is a convenient point to stop this review, whose intent was only to transmit the excitement of all these open questions in a field where many chapters must still be written, and the wonder that, for the first time, we may be looking through the haze, at converging clues about the origin of the solar system.