SCIENTIFIC RETURNS FROM A PROGRAM OF SPACE MISSIONS TO COMETS

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ABSTRACT

Cometary science is potentially at the crossroads of several interdisciplinary connections that have not been developed, only because our present knowledge of comets is incomplete or, at best, semi-quantitative.

The scientific return of a program of cometary missions would conceivably improve our understanding of most of the following topics: nature and size of interstellar dust, its origin and evolution; identification of new interstellar molecules; clarification of interstellar chemistry; accretion of grains into protosolar "cometesimals"; role of a T Tauri wind in the dissipation of the protosolar nebula; record of isotopic anomalies, better preserved in comets than in meteorites; cosmogenic and radiogenic dating of comets; cosmochronology and mineralogy of meteorites, as compared with that of cometary samples; origin of the earth's biosphere, and therefore the origin of life. Many unsolved problems related to cometary phenomena may also receive a final answer, like the understanding of the ionization mechanisms in comets, or the behavior of magnetized plasmas in space.

Such a cometary program would typically require about three rendezvous missions of progressive complexity; for instance, the second would require a successful docking, the third a sample return. If such a program is to be attempted before the end of this century, not many opportunities are available. Comet Halley is by far the best target for a first comet mission. It has a fairly reliable brightness and orbital behavior and has a gas production rate two orders of magnitude greater than any other comet whose passage can be reliably predicted before 2010. For this reason, more accurate and sensitive measurements of its chemical composition are possible. It is also the only reliable comet to display the full range of cometary phenomena.

Although two orders of magnitude fainter, many of the very short-period comets (there are 35 of them with periods from 3 to 7 years) have the orbital reliability for other cometary missions. In particular, although the production rate of gases of Comet Encke has considerably decayed during the last centuries, it still seems to have a rather large (kilometer-size) solid nucleus. Some of the most important records of past events could be more erased on Comet Encke than on Comet Halley; yet, a thin outer crust might protect pristine material that could be reached by digging. As an example of a very short-period comet with a reliable orbit, Comet Encke is therefore a good candidate for a sample-return mission, if it is preceded by an exploratory docking mission. However, in the present state of our ignorance, none of the other very short-period comets could be rejected as a scientifically less acceptable target for such a mission.

A program of space missions to comets may be justified by both strong scientific and public appeal. For this reason, before speaking about its scientific returns, I'd like to say a few words about its public appeal.

I perceive the public appeal of space exploration at two different levels -- the conquest of space for adventure and the search of the unknown for mystery. Let me first expand somewhat these two ideas as far as comets are concerned.

Conquest of Space for Adventure

As part of my duties at The University of Toledo, I give a class of Descriptive Astronomy for Non-Science Majors. Some of my students, who are fans of Star Trek and Star Wars, have told me that the expansion of mankind to all habitable worlds is the only legitimate final goal of space exploration. Space colonization is the last frontier for the young conquistadores of the 20th century, and to them, comets do not look very habitable. I told them that they were misinformed; on the contrary, the cometary environment may be the ultimate best place to develop space colonies. We will find there an abundance of all those chemicals needed to sustain life, already in almost the right proportions, because the H, C, N, and O atoms, which are the four basic constituents of our bodies, make up half of the cometary stuff.

However, even when we are ready for space colonies (it won't be before the 21st century anyway), they may become indeed an important by-product of space exploration, but I do not believe that they could ever become its final goal.

Search of the Unknown for Mystery

In hindsight, the colonization of the Americas was possibly a by-product of the renaissance, but the major achievement of the renaissance men was rather an expansion of knowledge yielding a better understanding of the nature of man. In the same way, our scientific and technological revolution has done it all over again on a grander scale, and the quest for relevance of the younger generation is nothing else but the first signs of a new world culture trying to integrate an expanding awareness of the world around us.

I therefore believe that, in our post-industrial society, our search for more basic values cannot do anything but grow, and the most fundamental question which transcends the colonization of space will remain the understanding of man. For this reason, the strongest public appeal of NASA's planetary exploration program will remain based on the search of the unknown, for mystery; and its ultimate goal will be to extend our awareness of what we are, in particular, to throw some light on the possible meaning of our presence in this corner of a forever very mysterious universe.

In the specific context of the planetary exploration program of the 1980's, I believe that the major mystery, that which has the strongest public appeal, is the question of how and why life appeared on the Earth, where it has (or could have) happened elsewhere in the planetary system, and whether the conditions needed to make life appear on the Earth were a natural and automatic consequence of the origin and evolution of the solar system.

In spite of the fascinating interest of the Viking landers' findings on Mars, they have brought, rightly or wrongly, a kind of anticlimax to the laymen's hopes of finding clues about life and its origin within the solar system. Those who believe in this anticlimax have certainly not pondered about what we are beginning to guess about comets. First, among the heavenly bodies, comets seem to contain the largest fraction (about one half) of H, C, N, and O molecules, already in almost the right proportions for life. Second, their analogy with carbonaceous chondrites suggests that they, also, contain prebiotic amino-acids (contrary to the Martian soil). Third, their highly elliptical trajectories introduce wide fluctuations in their crust temperature and in their ultraviolet irradiation, which may be the prerequisites needed to induce a prebiotic evolution. The crucial step from amino acids to viruses is the one we understand the least, and it is not unlikely that it could be somewhat clarified by cometary exploration. Fourth, it is not unlikely that a comet bombardment of the primitive Earth was the major or the only source of the biosphere (atmosphere, oceans and soil). Fifth, if comets were the source of the early life on Earth, it is not unlikely that this source of life has not dried up, and is still operating under our unsuspecting eyes. NASA's U-2 aircraft has collected cometary dust floating gently in the upper atmosphere, demonstrating that right now, cometary viruses could easily survive an atmospheric entry. Hoyle and Wickramasinghe (1977) have been bold enough to propose this chain of speculations and they are now checking the possibility that previously unknown viral infections have been periodically brought about by cometary dust. This conjecture gives a new dimension to the sudden world appearance of a new type of flu (that has been repeatedly observed) and a new twist to the medieval belief that comets are bad omens! Even if speculations of this type are not easily accepted by the scientific community, they play an important role in exploring the limits of our knowledge and in inducing the checks and balances needed to improve the paradigm of accepted science.

"New" Comets are the Most Pristine Bodies of the Solar System

Before reviewing the scientific returns from a program of space missions to comets, it is proper to summarize first what we know about comets.

The spectacular display of a comet's tail--that can be occasionally larger than one hundred million miles--is produced by the decay in the solar heat and light of a tiny object (tiny at least for astronomers) that we call the cometary "nucleus." It may be a couple of miles in diameter, and it can be described as a cold mixture of dust and snows, not only of <u>water</u> snows, but also snows of solidified gases of a gamut of volatile molecules mainly made of hydrogen, carbon, nitrogen, and oxygen. In short, the cometary nucleus is a "big dirty snowball." We have observed more than six hundred different comets so far, and we believe that there might still be billions of them, bound to the solar system but too far away to be directly detected.

Based on orbital as well as on abundance considerations, cometary nuclei are believed to be the most pristine bodies still around in the solar system, which makes them the probable building blocks from which most or all of the planets have been made.

Let's first summarize orbital evidence. The primary source of comets (see Fig. 1) seems to be a big reservoir gravitationally bound to the solar system which therefore participates in its motion--the Öpik-Oort cloud. We have observed so far approximately 100 "new" comets, coming straight from this cloud (transit time: 2 to 5 million years), but we have become progressively convinced that all secondary sources of comets are derived from this primary source. The 440 long and intermediate-period comets observed so far (periods from 200 years to more than 1 million

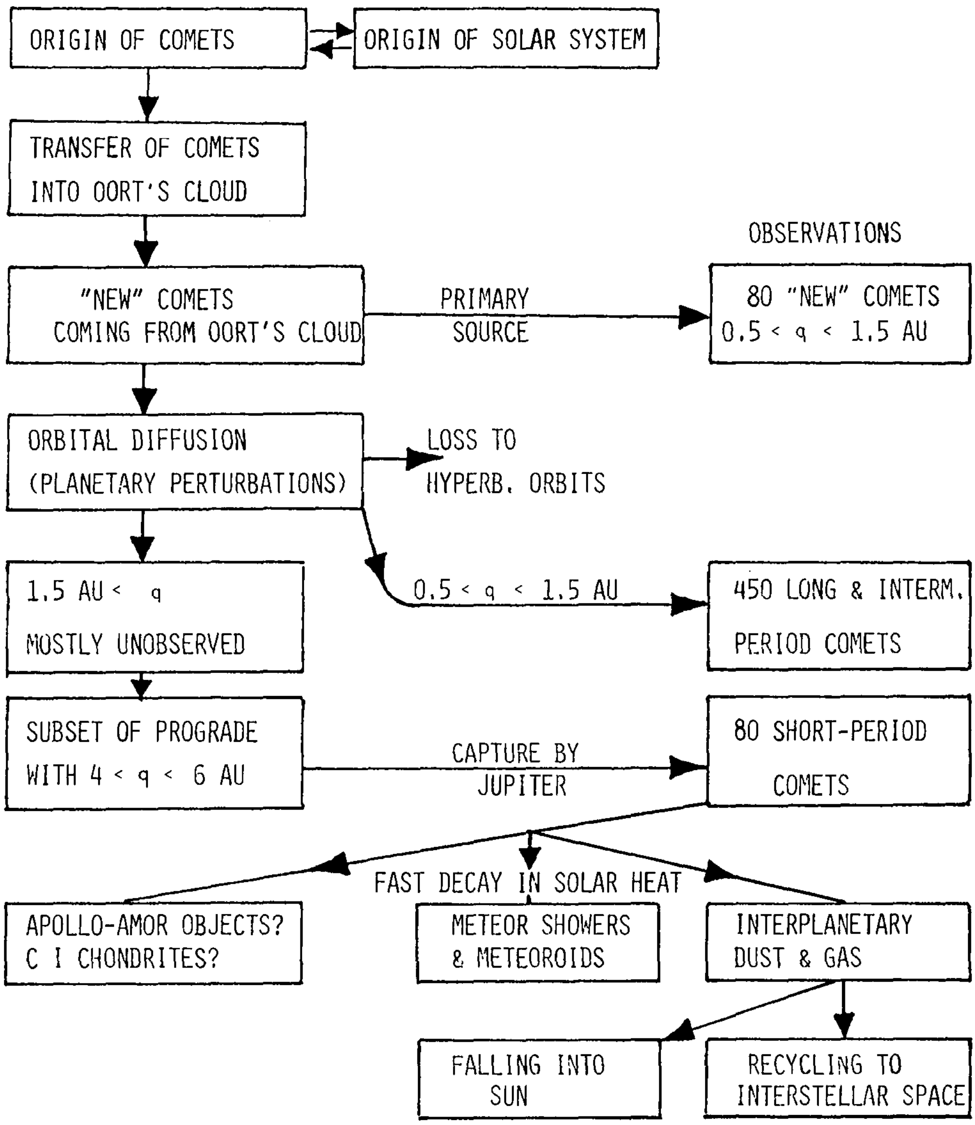


Fig. 1. The origin and evolution of comets--orbital evidence.

years) come from the orbital diffusion of "new" comets, induced by planetary perturbations. The 100 short-period comets have been captured from an unobservable subset induced by the same orbital diffusion: this subset includes those prograde comets whose perihelia are in the vicinity, mainly, of Jupiter (secondarily, of Saturn), so that these comets are easily captured by the giant planets. These three classes of comets all decay rapidly in the solar heat and either leave inactive comet nuclei, probably represented by the Apollo/Amor objects, stored on unstable orbits that eventually hit a terrestrial planet, or they decay into gas and dust. The dust eventually falls into the sun or is recycled to interstellar space, depending on its size.

Gas density is extremely low in the Öpik-Oort cloud. No model has ever been described in which its density could become high enough to accrete cometary nuclei in reasonable times. However, since comets are gravitationally bound to the sun, we believe that their origin is closely connected in time and space to that of the planetary system and that a mechanism of some sort must have transferred the newly-born comets into the Öpik-Oort cloud where these pristine objects have been stored until now--in the deep freeze of space.

A Possible Scenario of the Origin of the Solar System

Let's look more closely into the problem of the origins (Fig. 2). At this stage, all our scenarios are uncertain and can be contested. To simplify my discussion, I will stick to a plausible scenario, and will neglect some of the recent variations proposed by Cameron. If the solar system was formed by the contraction of an interstellar cloud, the interstellar grains present in the cloud followed suit and were covered by HCNO ices when the cloud became cold and opaque, but the subsequent

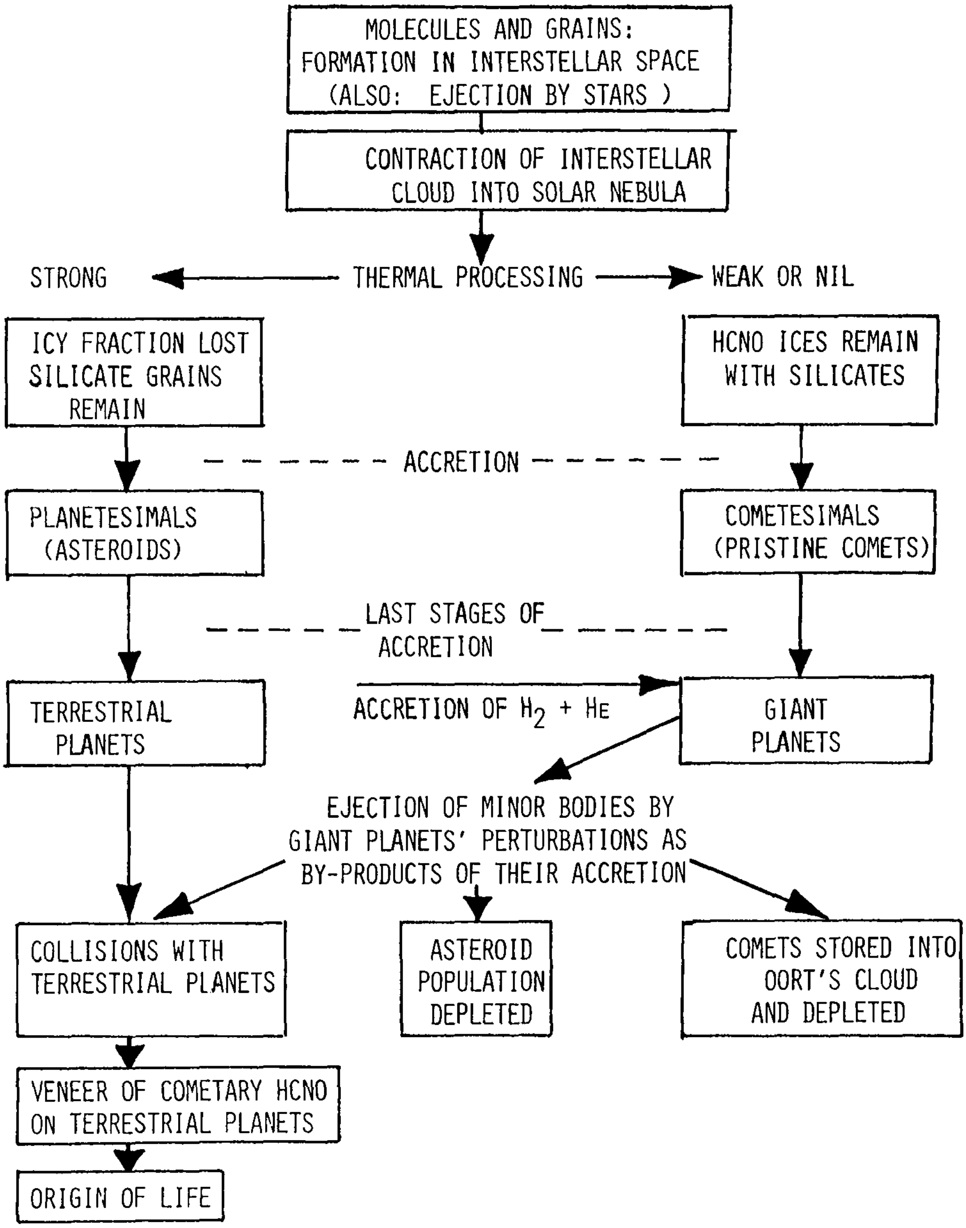


Fig. 2. The origin and evolution of comets--physical evidence.

heating of the cloud from its final contraction processed the icy grains. Some which were probably totally vaporized are now in the sun. Some which were heated enough to lose their icy mantles were accreted in rings within the mid-plane of the nebula and, because of gravitational instabilities, formed those planetesimals that accreted eventually into the terrestrial planets. Those icy grains that were not heated enough to lose their icy mantles, presumably those in the outer parts of the nebula, formed cometesimals (or pristine comets), containing roughly as much HCNO molecules as metallic silicates--in other words as much volatile snows as non-volatile dust. These comets were assumedly the building blocks of the giant planets, at least Jupiter and Saturn, with a supplementary accretion of those gases still available in the solar nebula. Maybe the accretion of Uranus and Neptune took too long, and the gaseous nebula had totally dissipated before the final stages of their accretion; but this is another problem.

The important fact is that in this scenario, the Öpik-Oort cloud becomes a necessary consequence of the accretion mechanism. As soon as the giant planets developed a gravitationally significant core, they ejected minor bodies out the solar system and caused cometesimals to be stored in the Öpik-Oort cloud. Ejected at random, a good fraction of these cometesimals passed through the inner solar system, and their collisions with the terrestrial planets built a veneer of cometary HCNO on these planets.

In a recent review paper, Anders and Owen list many clues showing that the veneers on Earth and Mars came from the same "objects," whatever they are. The closest objects handy in our museums are the C3V carbonaceous chondrites; Anders and Owen were, of course, not able to compare the postulated objects with comets, because we don't have comets in our museums. Their study used a powerful tool developed for meteorites--comparing elementary abundances with solar abundances and deducing the history of the depletions from the volatile properties of the elements and of their chemical compounds. We cannot yet do that for comets, but we are not far away. I have recently (see Table 1) presented evidence that comets have kept much more volatiles than any other body of the solar system, if we exclude the giant planets where gravitation has probably played a large role.

Comets and the Origin of Life

As a matter of fact, the HCNO abundances in comets (Table 1) seem to be in the same general range as that needed to develop the delicate chemistry of life; in particular, it seems an excellent mixture to make amino acids. In Table 1, I have represented life by the standard chemical analysis of protoplasm, normalized for oxygen = 10 (I could not use silicon for normalizing, since we do not have silicon in our bodies). I believe that in particular, there is too much hydrogen to initiate life easily in the giant planets, whereas there is not enough hydrogen and too much oxygen in the crust of the Earth and of Mars. It is much easier to build up the delicate and fragile molecules needed for life by starting with a mixture about in the right proportions; of particular importance is a well chosen redox ratio (oxygen-to-hydrogen ratio), especially when dealing with solutions in water, as in the primeval oceans. In this respect, comets and carbonaceous chondrites seem to be much better sources for the biosphere (oceans and atmosphere of the Earth) than is Jupiter's atmosphere or the crust of the terrestrial planets.

Table 1. ELEMENTAL ABUNDANCES IN SOLAR SYSTEM (NORMALIZED TO SILICON = 1)

	ATMOSPHERES OF LARGER OBJECTS		SMALLER OBJECTS			LIFE*****
	SUN JUPITER? SATURN?	URANUS NEPTUNE	COMETS ***	C I CHONDRITES ****	EARTH'S CRUST	PROTOPLASM
H	30,000	100*	15	1.5	0.04	27.2
C	13	2**	3	0.7	0.02	2.1
N	3	?	>0.1	0.05	0.0001	0.3
O	21	?	21	7.5	2.8	10.0
Si	1	1	1	1	1	----

*Polodak (1976), consistent with **Owen and Cess (1975)

***Delsemme (1977); ****Mason (1971); *****Normalized to oxygen = 10

Do comets contain amino-acids? Nobody knows, but from the present data on C I chondrites, it is tempting to predict they do. We do not know much about comet chemistry, because even under the best conditions, we have never seen a comet nucleus as more than a pinpoint of light.

In the cometary spectra, we do not see the molecules that sublimate from the nuclear ices, but only those fragments, atoms and radicals, left over from their violent interaction with sunlight and the solar wind (Table 2). Only recently has radio astronomy been able to detect parent molecules, namely HCN, CH_3CN, and H_2O; and in Toledo, we have developed circumstantial arguments suggesting that CO_2 is also one of the major constituents. However, we are far from getting accurate quantitative analyses.

Aging and Decay of "New" Comets

Now, only "new" comets, coming straight from the Öpik-Oort cloud can be guaranteed to be primitive objects with a pristine surface. Unfortunately, we cannot use them for a cometary mission, because we discover them perhaps six weeks, or at best six months, before their first perihelion passage.

Oort has established (Fig. 3) the only clear-cut differentiation linked with cometary aging and decay. The average exponent in the law relating cometary brightness to radial distance from the Sun grows with age. When combined with the sublimation theory of the nucleus, the exponent tells the average temperature of sublimation, which remains nearly constant for a particular comet. In turn, the temperature can be related to the fractional distillation of the snows in the upper layers of the nucleus. Do not forget, however, that the nucleus may remain extremely cold inside, and that pristine interstellar grains might possibly be

Table 2a. OBSERVED CONSTITUENTS IN COMETARY HEADS AND TAILS

ORGANIC:	C, C_2, C_3, CH, CN, CO, CS, HCN, CH_3CN;
INORGANIC:	H, NH, NH_2; O, OH, H_2O, S;
METALS:	Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V, Si;
IONS:	C^+, CO^+, CO_2^+, CH^+, CN^+; N_2^+; OH^+, H_2O^+; Ca^+
DUST:	Silicates (Infrared Reflection Bands)

Table 2b. REPORTED NEGATIVE RESULTS (MAINLY RADIO SEARCHES)

ORGANIC:	H_2CO, CH_3OH, $CH_3O\text{-}CH_3$; $CH_3\text{-}C \equiv CH$; CH_4 (Infrared)
ORGANIC WITH N:	HNC, HNCO, $CH \equiv C\text{-}CN$, $CN\text{-}CH_2\text{-}CN$,
INORGANIC:	NH_3, SiO_2

(Source: Delsemme (1977) supplemented by recent UV results from Comet West)

I DIFFERENTIATION WITH AGING, DETECTED BY BRIGHTNESS DEPENDANCE ON DISTANCE :

B REDUCED BRIGHTNESS (FOR: $\Delta = 1$ A.U. FROM EARTH)

B_0 ABSOLUTE BRIGHTNESS (ALSO: R = 1 A.U. FROM SUN)

$$B = B_0 R^{-N}$$

$\bar{N}$	ORBITAL FEATURES	TEMPERATURE	INTERPRETATION
2.8	"NEW" COMETS	110°K	SUBLIMATION CO_2
3.7	"FAIRLY NEW"	170°K	CO_2 DISAPPEARS
3.8	"OLD" COMETS	180°K	AND H_2O SUBLIMATES
4.2	PERIODIC	200°K	CRUST IS FORMING (ALBEDO DIMINISHES)

II DUST / GAS RATIO (DUST-SIZE DISTRIBUTION VARIES)

III CO^+ / ($CN + C_2$) RATIO (IONIZATION EFFICIENCY IS SIZE-DEPENDENT)

Fig. 3. Physical differences among comets.

found by digging a couple of feet into the most extinct comets. However, "new" comets display a full range of phenomena that are sometimes, but not always, found in periodic comets.

<u>Possible Choices for a Cometary Mission</u>

Although a periodic comet, Comet Halley does show this full range of phenomena--dusty tail, plasma tail, C_2 + CN coma, "activity," expanding halos, etc. In the present state of our ignorance, we believe that these signs mean that Halley still is a rather young comet, if not pristine. We believe it is the best choice for a first cometary mission because we can rely on its orbit and because it is much brighter than some other opportunities, such as Giacobini-Zinner, Tempel 2, and Encke. For instance, we believe that Comet Encke is a very old comet, since its steady decay has been observed during the last two centuries, but we have no way of deciding whether the scientific return of such a mission would be marginally or considerably lower than that of a mission to Halley; lower production rates may mean that a smaller number of minor constituents would be detected by our instruments.

<u>Scientific Return of a Mission Program</u>

Let's consider in detail what would be the scientific return of a cometary mission program. I say a mission program because I believe that, in order to achieve a large fraction of the objectives I am going to discuss, we need at least two and probably three missions, including one or two successful dockings with the nucleus and one sample return of snow and dust. If we do that, we'll have so many new answers and so many multidisciplinary connections, that the traditional problems of cometary physics may become passé and insignificant. For this reason, I want to use the unconventional approach of ignoring the traditional problems in the first place, in order to open all interdisciplinary connections first.

Let's get started with interstellar dust and gas (Table 3). We can reasonably assume that comets still contain interstellar grains. Therefore we can gain some insight on the nature and size of interstellar dust (including its icy mantle). We can also hope that some record of the dust's origin has been preserved in grains, for instance through some isotopic ratios; this would tell us the story of its origin. Depending on the depth at which we collect the dust, we might find variations in the aging of the grains, in particular in their icy mantles. A record of cosmic-ray damages may be preserved in the first few feet of crust of any comet nucleus. This will possibly explain the chemical nature of the triggering of the activity phenomena in comets.

I will not discuss in detail the use of the proposed instruments that I have included in Tables 3-6 (those that are unlikely to be included in a first mission are in parentheses). You should however notice that the neutral mass spectrometer (for the volatile fraction--all HCNO molecules and isotopes) and the x-ray fluorescence spectrometer (for the metals present in the non-volatile fraction) appear again and again, which demonstrates their fundamental and unique importance (with imaging) in the rendezvous mission, before any docking or sample return. We should not forget to add the interstellar molecules to this picture, since we are likely to detect those major interstellar molecules that the radio astronomers have missed so far, just, for instance, because (like CO_2) they cannot be detected by their radio spectrum. Quantitative

Table 3. INTERRELATIONS BETWEEN INTERSTELLAR AND COMETARY GRAINS

SCIENCE OBJECTIVES	ASSUMPTIONS
Nature and size of interstellar dust	Comets still contain interstellar grains
Origin of dust (In stars? In space?)	Record of dust origin preserved in grains
Evolution of dust (Aging of icy mantles)	Record of cosmic ray damages, preserved in surficial ices
Age of cometary grains	Isotopic ratios change with galactic age

INSTRUMENTS NEEDED	SCIENCE RETURN
Dust particle counter and analyzer	Dust mass distribution; dust composition
Orbital x-ray fluorescence and collected dust analyzer	Element abundance ratios for non-volatiles
Neutral mass spectrometer	a) Element abundance ratios for H, C, N, O b) Isotopic ratios c) Volatile molecule identifications

HOPES:

1. Identifying new major interstellar molecules.
2. Starting quantitative interstellar chemistry.
3. Clarifying its conceptual basis.

analyses of cometary ices would form a foundation for quantitative interstellar chemistry, whose present conceptual basis is still shaky.

Another interdisciplinary connection is that of meteorites (Table 4). Meteoritics has been extraordinarily successful because there were samples in our museums. We could do the same with comets if we brought back a spoonful of cometary dust and snows. The analogy between comets and carbonaceous chondrites as given by Herbig is well known: if a C I chondrite were put in space, vaporization by solar UV would yield all the radicals observed in comets. Of course this is only a qualitative statement. Quantitatively I have recently shown that comets are more pristine than C I chondrites because they contain 3 to 10 times as much HCNO molecules (Table 1). Therefore I believe that all techniques developed for meteorites like cosmochronology, mineralogy of samples, etc. will work successfully for cometary samples. We can probably do even better: the record of the origin of the anomalous isotopic ratios must be better preserved in comets, because less fractionation took place, mainly for the important H, C, N, O atoms, that are one half or more of the cometary stuff. And here, we certainly should not neglect the prebiotic chemistry, that seems guaranteed to work in comets because we have the proper HCNO ratios, in particular the proper (so important) oxydo-reduction ratio.

Let's consider now (Table 5) the interrelations with the protosolar nebula; we have two hypotheses that seem to disagree completely. Either the cometary ices came from the icy mantles of interstellar grains or they condensed later on the sandy grains that were the high temperature condensates of the solar nebula. A third possibility exists that has never been clearly expressed--the icy mantles were not destroyed but

Table 4. INTERRELATIONS BETWEEN METEORITES AND COMETS

SCIENCE OBJECTIVES	ASSUMPTIONS
To explain the apparent analogy with meteorites	The analogy with C I chondrites is not coincidental
Origin of isotope anomalies	Record of isotope origins better preserved in comets
Cosmochronology Mineralogy	Techniques developed for meteorites will work for cometary samples

INSTRUMENT NEEDED	SCIENCE RETURN
Neutral mass spectrometer	HCNO and other isotopic ratios
	Volatile molecule identifications
	Search for organic materials detected in meteorites, amino acids, etc.
Orbital x-ray fluorescence collected dust analyzer	Element abundance ratio for non-volatiles
(On-board mineralogy) (Sample return)	Classification of cometary minerals and rocks in framework of meteoritics

HOPES:

1. Prebiotic chemistry.
2. Origin of life.

Table 5. INTERRELATIONS BETWEEN SOLAR NEBULA AND COMETARY CONDENSATES

SCIENCE OBJECTIVES	ASSUMPTIONS
Condensation of protosolar nebula	Comets contain those gases that condensed onto cooler grains from the solar nebula
Temperature of comets' formation	Presence or absence of gases can be used as cosmothermometer
Nature of planetesimals	Pristine comets are those planetesimals from which planets were accreted
Depletion of solar nebula (By T Tauri wind?) (In exocone?)	Record of gaseous fraction is kept by condensed volatiles

INSTRUMENTS NEEDED	SCIENCE RETURN
Neutral mass spectrometer	1) HCNO 2) Isotopic ratios 3) Volatile molecules
IR radiometer	Temperature & emissivity of nucleus
(On board mineralogy)	Comparison of high and low temperature condensates

HOPES:

Fractionation of HCNO molecules is key to HCNO ratios used by life.

processed and modified by accretion of snowy condensates of the solar nebula. We have a way to know: it is to go and check with a comet. We will settle by the same token the temperature of comet formation. If we do not find any CO or CH_4, then this temperature was higher than 50°K. If CO_2 is present in the cometary snows, then the primeval temperature was smaller than 100°K, etc. This will tell us the nature of the pristine planetesimals that were rather "cometesimals," i.e., the building blocks from which all planets were accreted. The record of the gaseous fraction of the nebula is probably also kept by the volatiles that condensed within the cometary nuclei; therefore we will be able to say whether the solar nebula was differentiated before condensation and accretion. For instance, we could unravel the history of a possible hydrogen depletion and establish whether it was due to the violent solar wind of the T-Tauri phase of the early sun, or rather to the rotation of the nebula, that could induce an H_2 and He loss in an exocone analogous to the terrestrial exosphere (Table 6). Of course, we hope that this fractionation of the solar nebula by different processes which are not yet clearly understood is the key to explain those HCNO ratios that were needed later to get life started.

Imaging will also play a decisive role, because these pristine cometesimals are a brand-new class of heavenly bodies that we have never seen. Perhaps Comet Encke's crust will look much like my Figure 4 (which is, you have guessed, a picture of one of the satellites of Mars, which have the same size as cometary nuclei) but I presume a cometary nucleus would look much more sophisticated than this, with valleys filled up with vaporizing glaciers, giant séracs with fragile structures defying gravity (because the gravity at the surface of a cometary nucleus is

Table 6. INTERRELATIONS BETWEEN COMET NUCLEI AND ORIGIN OF SOLAR SYSTEM

SCIENCE OBJECTIVES	ASSUMPTIONS
Elucidate chemistry and morphology of "planetesimals"	Comets are "planetesimals," that is, pristine building blocks of early solar system
Reconstruct the accretion history of the planets	Comets were put in "cold storage" in Öpik-Oort cloud, as a residue of planetary accretion

INSTRUMENTS NEEDED	SCIENCE RETURN
Imaging	Size, shape, rotation Optical properties Physical heterogeneities
Neutral mass spectrometer	Chemistry of volatile fraction Isotopic ratios H, C, N, O, other
Orbital x-ray fluorescence; Collected dust analyzer	Element abundance ratios for non-volatiles
Radar altimeter	Mass Dielectric constant Roughness
(On board mineralogy) (Sample return)	Nature of cometary minerals and rocks

HOPES:

Planetesimal chemistry is key to planets' accretion.

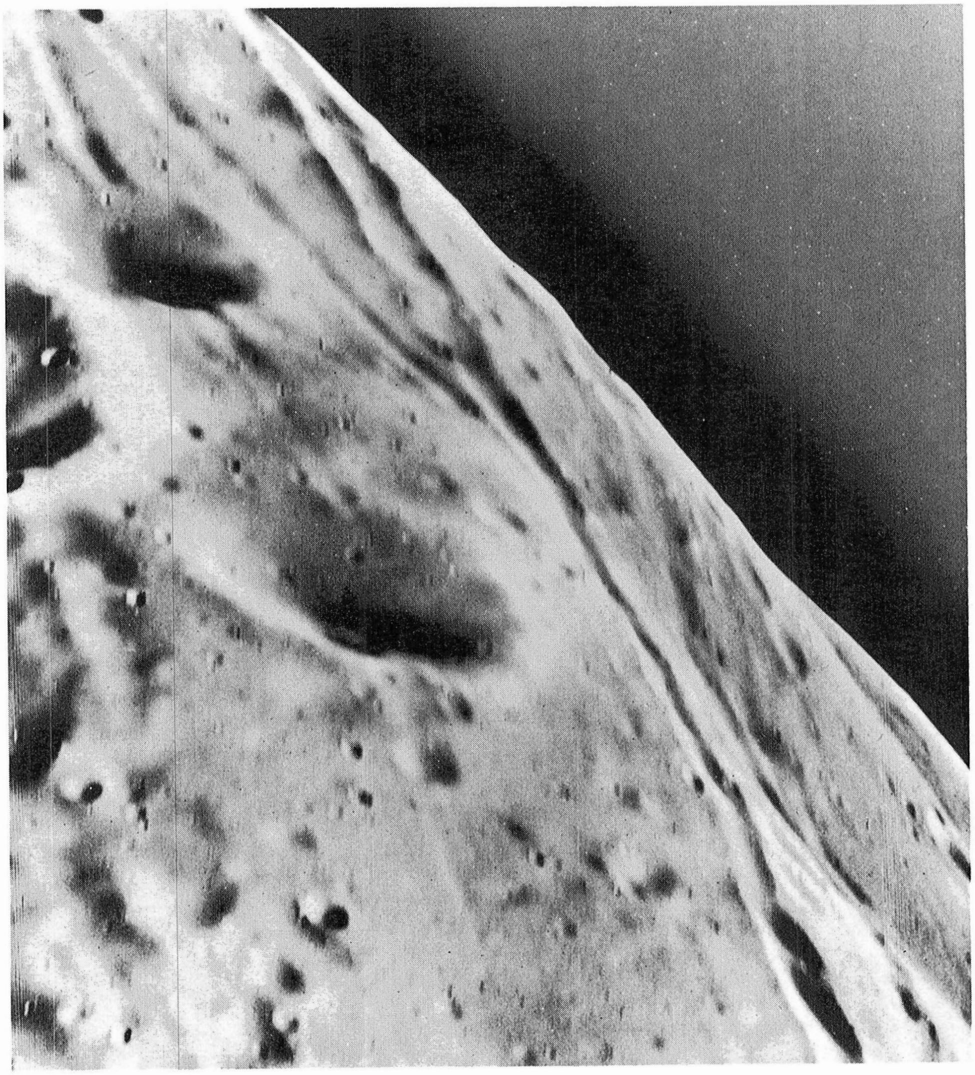


Fig. 4. Photograph of Phobos.

some ten-thousand times lower than terrestrial gravity). But we would see a forever-changing landscape (Table 7) because the nucleus steadily decays: the atmosphere is an exosphere that drags dust away and that reaches collisionless effusion in vacuum only a few thousand miles away.

Here we reach the interrelations with meteors, meteoroids, and interplanetary dust. Is the nucleus like a raisin bread? Are the raisins going to become bolides? Do comets decay steadily into dust? Or do they build either a rocky core, or an icy core behind a crust? What is the cohesive strength of the core? What is the role of the rotation in the observed break-ups? What is the nature of the cometary outbursts? I have in Fig. 5 a list of eleven different hypotheses proposed during the last twenty-four years to explain the origin of cometary outbursts. You do not have to try to understand all these hypotheses in detail. My point is that no single convincing interpretation has been proposed so far. However, most of these interpretations are based on a structural complexity of the nuclear region which I have tried to suggest by my drawing of an outburst. This drawing is only meant to symbolize the impact that the first real picture would have, by showing for the first time an entirely unknown, new class of heavenly body. We have experienced that a few times only; you certainly remember the emotional impact when the first real pictures of Mars were substituted for the drawings of the canals of Lowell and Schiaparelli. This would be something of that order, that would enlarge our awareness and our comprehension of another facet of the universe.

Let's turn now to the study of the transient phenomena induced by the solar wind and ultraviolet light (Table 8). Cometary tails

Table 7. DECAY AND FINAL OUTCOME OF COMETARY NUCLEI: INTERRELATIONS WITH METEORS AND INTERPLANETARY DUST

SCIENCE OBJECTIVES	ASSUMPTIONS
Characterize physical decay of nucleus during passage by the sun	Icy conglomerate, irregular structure, low cohesive strength; sublimation drags dust away
Characterize final outcome of cometary material	Meteoroid streams, some bolides, and interplanetary dust are non-volatiles lost by comets.

INSTRUMENTS NEEDED	SCIENCE RETURN
Imaging	Disintegration of surface Physical heterogeneities Cohesive strength Role of rotation in break-up Nature of outbursts
IR radiometer	Temperature and emissivity
Radar altimeter	Roughness and heterogeneity
Near IR spectrometer	Chemical homogeneity Mineral signatures

HOPE:

Imaging a brand-new class of bodies, more primitive than planets, that have accreted in a gravitation field smaller than 10^{-4}g.

Cometary outbursts have been alternately explained by:

1. excitation by activity outbursts of the sun (Beyer 1953).
2. vaporization of pockets of more volatile material like methane or carbon dioxide (Whitney 1955).
3. explosive radical reactions (Donn & Urey 1956).
4. excitation by corpuscular streams of the sun (Vsekhsviatskii 1966).
5. collisions with interplanetary shock waves (Eviatar *et al*. 1970).
6. tidal action of the Sun and Jupiter (Pittich 1972).
7. collisions with large meteoroids (Sekanina 1972).
8. cosmic rays from solar flares triggering the reaction of unsaturated hydrocarbons (Shul'man 1972).
9. transition from amorphous to cubic ice (Patashnik *et al*. 1974).
10. rotational breakup (Kresak 1974).
11. radiative chemical processes (Shul'man AAK 24, 91, 1975).

This mere enumeration is enough to show that no single convincing interpretation has been proposed so far.

This fanciful drawing of an outburst suggests :
a) structural complexity of nuclear region
b) impact of first actual picture of a new body

Fig. 5. Origin of cometary outbursts.

Table 8. BEHAVIOR OF INTERPLANETARY PLASMA

SCIENCE OBJECTIVE	ASSUMPTIONS
Insight into all energetic phenomena involving magnetized plasmas	Cometary tails are probes of interaction of two plasmas in conditions impossible to duplicate in the lab
Source of ionization in comet heads	Electric currents, magnetic fields are induced in atmosphere
Characterize the interaction of solar wind with comets	There is a bow shock; there is a contact surface; ions are accelerated into tail
Explain apparent wave motions, twists and knots seen in tail	Induced by plasma interaction

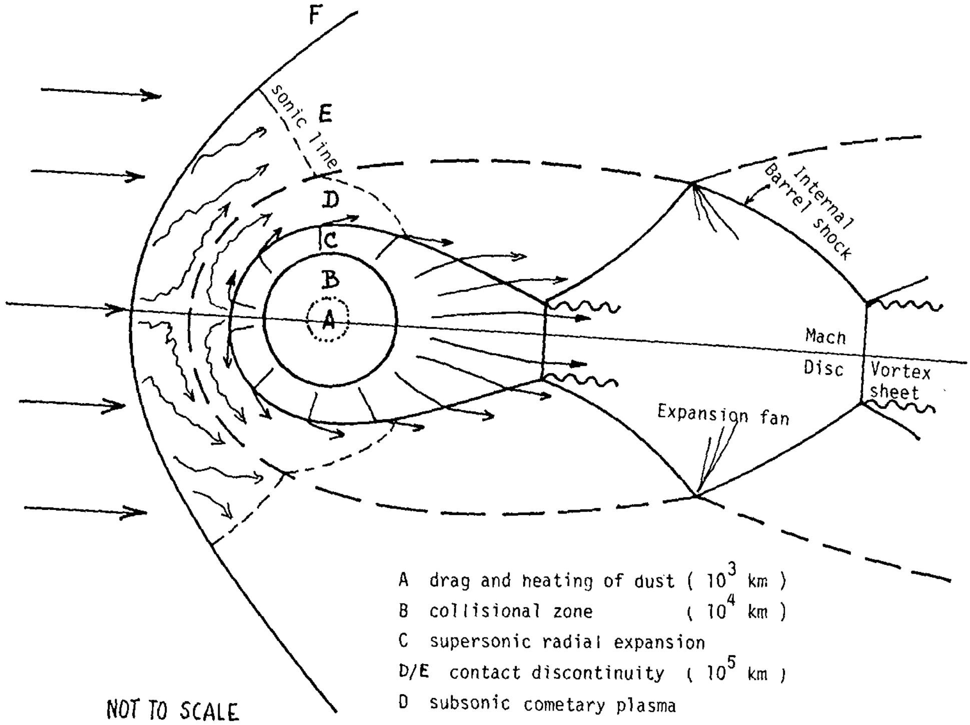
INSTRUMENTS NEEDED	SCIENCE RETURN
Thermal ion spectrometer	Ionic composition, temperature and velocity
	Ionization mechanisms near nucleus
Ion mass and velocity/solar wind analyzer	Acceleration of ions to form tail
	Bow shock, contact surface, instabilities
Magnetometer	Magnetic properties of ionosphere
	Magnetic field of nucleus
	Interaction with solar wind
Plasma wave detector	Field instabilities and waves
	Ionization and acceleration mechanisms
Electron analyzer	Ionization phenomena near nucleus

have already been used as probes of the solar wind but our models are simple-minded. We predict, but have never seen the bow shock, ahead of the comet. We could detect it easily even in a flyby mission. We also speak in terms of a contact surface which separates the cometary plasma from the solar wind plasma, but we know that cometary neutrals diffuse through it unaffected because they do not feel the magnetic field, and they can be photoionized later; therefore none of our models is satisfactory. We would like also to determine how the ions are accelerated into the plasma tail, and to explain the apparent wave motions seen in the tail; all this could be easily measured.

Fig. 6 is here only to remind you that the cometary ionosphere is a very complex animal. At this scale, the nucleus is too tiny to be seen. The center represents the zone where all atoms and molecules still collide, that is, where charge-exchange reactions take place. Practically none of the details of this theoretical model have ever been seen and identified.

Finally, I come to what the physical study of comets was all about some ten years ago, when we were using optical spectra only (Table 9). What are the parent molecules of the cometary radicals? How are they photodissociated, ionized, or otherwise transformed? How are so many ions produced near the nucleus? What are the mechanisms of decay? All of these problems would become easy if we had time sequences of mass spectrometer analyses when we were approaching the nucleus.

We must use a careful strategy that I will only briefly suggest by Figure 7. The x-axis represents the months before and after perihelion. The y-axis is the logarithmic distance to the nucleus, and I propose to move slowly back and forth to study the time variation of each observed



A drag and heating of dust (10^3 km)
B collisional zone (10^4 km)
C supersonic radial expansion
D/E contact discontinuity (10^5 km)
D subsonic cometary plasma
E subsonic solar wind plasma
E/F bow shock (10^6 km)
F supersonic solar wind plasma

Adapted from Wallis and Dryer, Ap. J. 205, 895.

Fig. 6. Interaction of comets with the solar wind.

Table 9. THE NEUTRAL AND IONIZED ATMOSPHERE

SCIENCE OBJECTIVE	ASSUMPTIONS
Parent molecules of observed radicals	Parents produced near nucleus by sublimation of frozen gases
Atmospheric chemistry	Charge-exchange reactions reshuffle molecular species
Ionic composition and temperature	Ions are produced very near the nucleus
Identification of ionization mechanisms near nucleus	Ionization mechanisms rely on charge-exchange reactions
Interaction with solar wind	Shock wave and contact surface can be detected by discontinuities

INSTRUMENTS NEEDED	SCIENCE RETURN
Neutral mass spectrometer	Radial variation of abundances yields understanding of coma's chemistry and ionization mechanisms
Thermal ion spectrometer electron analyzer	Ionization mechanisms
Ion mass and velocity solar wind analyzer	Ion acceleration mechanisms; interaction of solar wind; bow shock; contact surface; instabilities
UV spectrometer	Neutral and ion production rate Scale lengths of species Dust distribution and albedo

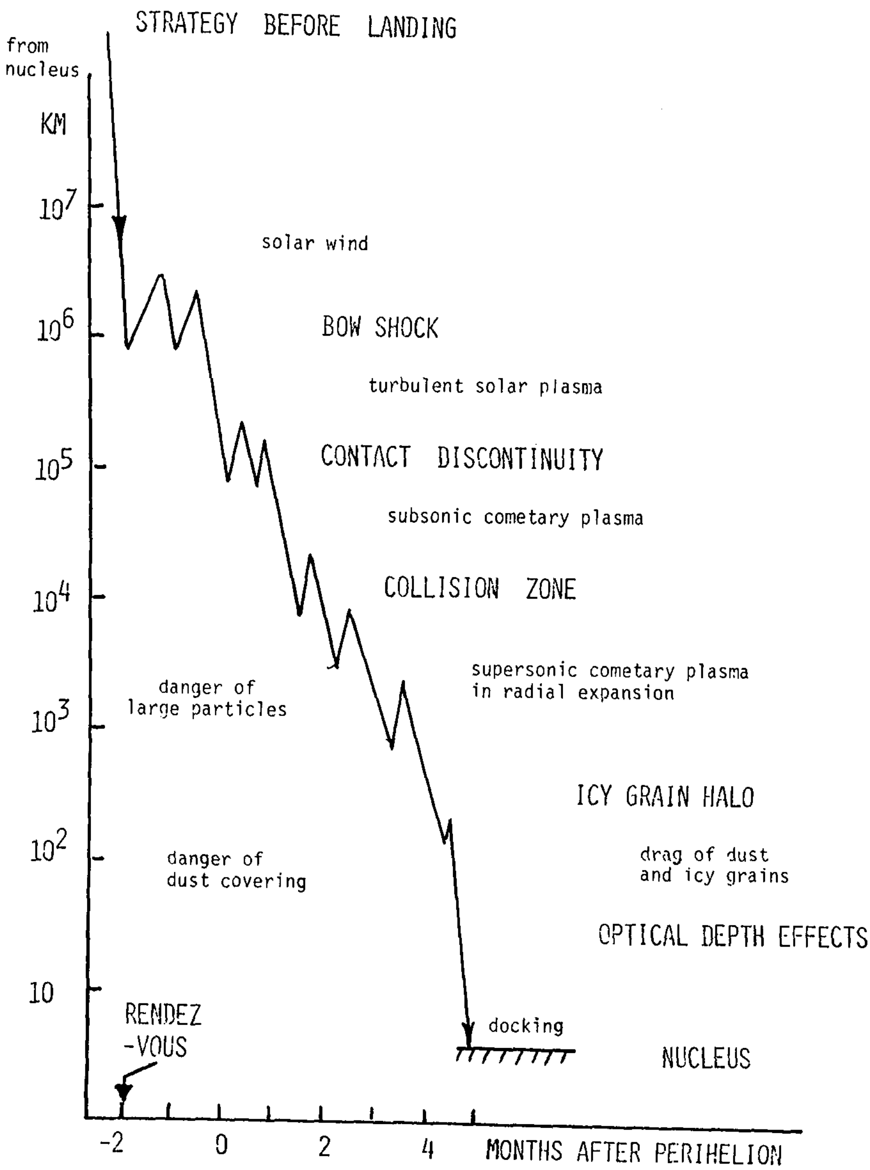


Fig. 7. Exploration strategy before landing.

transition or discontinuity. The nearer to the nucleus, the more exciting the results, the closer to pristine molecules, the more difficult and risky. A first rendezvous should certainly terminate by a tentative landing, or rather by a docking (landing has no meaning in a gravity field of 10^{-4} g) but only after all the essential experiments have been performed. The reason is that we have to design the docking operation before having seen the nucleus, therefore it is more risky than anything ever done before. The most important use of the mass spectrometer and x-ray fluorescence analyzer takes place between 1000 and 100 km from the nucleus. Beyond 1000 km, the phenomena are too much influenced by outside perturbations; within 100 km, the danger of dust covering is large.

I have alluded already to the origin of life: I would like to emphasize in Table 10 the three connected questions where the scientific returns seem most likely. First, the problem of the cometary depletions in H, C, N versus O. We have hints that these depletions have induced the conditions needed to reach the delicate balance of prebiotic chemistry. Second, we should check the nature of all HCNO molecules; I believe that we will certainly find amino acids as in carbonaceous chondrites. (Other scientists go further and believe we could find viruses!) Finally, the study of all isotopic ratios linked with all elementary depletions will tell us whether comets or carbonaceous chondrites or both were a late accretion veneer on the Earth and the source of the biosphere.

Finally, Table 11 summarizes the scientific objectives of a cometary mission. I have listed the science returns in front of the correlation with other fields--interstellar dust versus cometary grains--interstellar gas versus cometary gases--meteorites versus comets for the isotopic anomalies and the presolar origin of grains--building blocks of the solar system, exemplified by the cometary nucleus--final outcome of the nucleus,

Table 10. ORIGIN OF LIFE

SCIENCE OBJECTIVE	ASSUMPTIONS
HCNO abundances in comets	The cometary depletion in H, C and N versus O may duplicate the delicate balance to induce prebiotic chemistry
Nature of HCNO molecules in comets	Origin of amino acids
All isotopic ratios	A late accretion veneer of comets may be the source of the terrestrial biosphere

INSTRUMENTS NEEDED	SCIENCE RETURN
Neutral mass spectrometer (range up to 250 AMU)	HCNO, rare gas and other isotopic ratios
	Large molecule identifications
	Search for amino acids, etc.

HOPE:

Checking Hoyle and Wickramasinghe's hypothesis: in comets, amino acids and nucleotides have evolved into viruses or protoviruses. (Present terrestrial viruses are bacterial parasites; however, in our ignorance of the early evolution of bacteria, it seems likely that they were preceded by simpler forms looking like viruses that were able to survive without bacteria: the "protoviruses.")

Table 11. SUMMARY OF POTENTIAL SCIENCE RETURNS

CORRELATION WITH:	SCIENCE RETURN:
Interstellar dust (stellar evolution)	Nature, size distribution, origin, evolution and age of cometary grains
Interstellar gas (chemistry of interstellar clouds)	Molecular abundances in volatiles; discovery of new molecules undetected by radio-astronomy
Meteorites (origin of presolar nebula)	Comparison with primitive meteorites, isotopic anomalies (in particular for H, C, N, O), cosmochronology, mineralogy
Accretion history of planets (origin of solar system)	Bulk nucleus: chemistry, condensation, thermal history; anisotropy, morphology, differentiation; core, mantle, crust "geology"
Meteors and meteoroids (final outcome of interplanetary matter)	Cohesive strength of nucleus; scale of heterogeneities (raisin-bread model), "activity", decay, snow sublimation, dust drag, size distribution of lost fragments
All magnetized plasmas in astrophysics	Insight in plasma behavior through interaction with solar wind; ionization sources, motions, twists and knots in tails, plasma waves
Physical chemistry	Photochemistry and charge-exchange chemistry of cometary radicals: parent molecules: ionization mechanisms
Origin of life	Origin of depletions from HCNO abundances; prebiotic chemistry of HCNO molecules; source of biosphere

into meteoroid and meteorites--cometary plasma, versus all plasmas from the bow shock of planet Mercury to the magnetohydrodynamics of the pulsars--the physical chemistry of the cometary coma to elucidate basic mechanisms and phenomena--last but not least, the origin of life and the possible source of the biosphere, through prebiotic chemistry.

I have just described a very heavy program, and it is filled with unknowns and uncertainties. This is a sure sign that we have delineated a virgin territory. We should not be afraid of all the uncertainties but be encouraged by them. After all, if there were no unknowns, it would not be worth doing.

Mission Tradeoffs

What is the trade-off if we choose to go to a less pristine comet? This is an almost insoluble question. For instance, would we lose something in the primitive nature of the accessible crust if we switched from Comet Halley to Comet Encke? Certainly yes. How much? Nobody knows. Comet Halley is more pristine and much brighter than Encke. As such, it has had much more impact on the minds of men than any other comet and for this reason, if we don't use its 1986 perihelion passage for exploration, the people will wonder--too late-- why NASA isn't doing something. But NASA knows that, and intends to do something. If, for budgetary reasons beyond our control, we cannot do a rendezvous with Comet Halley, we should at least do a Comet Halley flyby and go on to a rendezvous with Comet Encke or some other short-period comet such as Tempel 2 or Giacobini-Zinner. This is an intriguing possibility that, I understand, is going to be explored soon in more detail by JPL.

Conclusion

To remind you how Halley is historically linked with our western culture, I will finish on a well-known primitive image of the 1066 A.D. passage of Comet Halley found in the 11th century Tapestry of Bayeux, France (Figure 8). It happens that I have used this picture for the cover of the book that I have just published (1977). As you see, this figure is also shameless publicity for the book, which stems from IAU Colloquium No. 39 and is available only through The University of Toledo Bookstore. In my drawing here, there is a missing caption, written in Latin on the Bayeux Tapestry, that reads "isti mirant stellā," these (people) wonder because of the star. In the next scene, the tapestry depicts an astrologer telling King Harold of the bad omen brought by the comet. As everybody knows, King Harold was going to be killed a few months later at the Battle of Hastings. However, I prefer the scene I have used because it shows a pretty drawing of Comet Halley (with some imagination, you can identify its coma, its dust tail, and even its very narrow plasma tail with its knots and twists in the central part of the dust tail). Furthermore I prefer these faces, because they show exactly what astronomy is all about, wondering in front of an immense unknown universe. Mankind has not changed in nine centuries; there we were in 1066 A.D., there we will be again in 1986, wondering whether Comet Halley could throw some light on man's condition and origin.

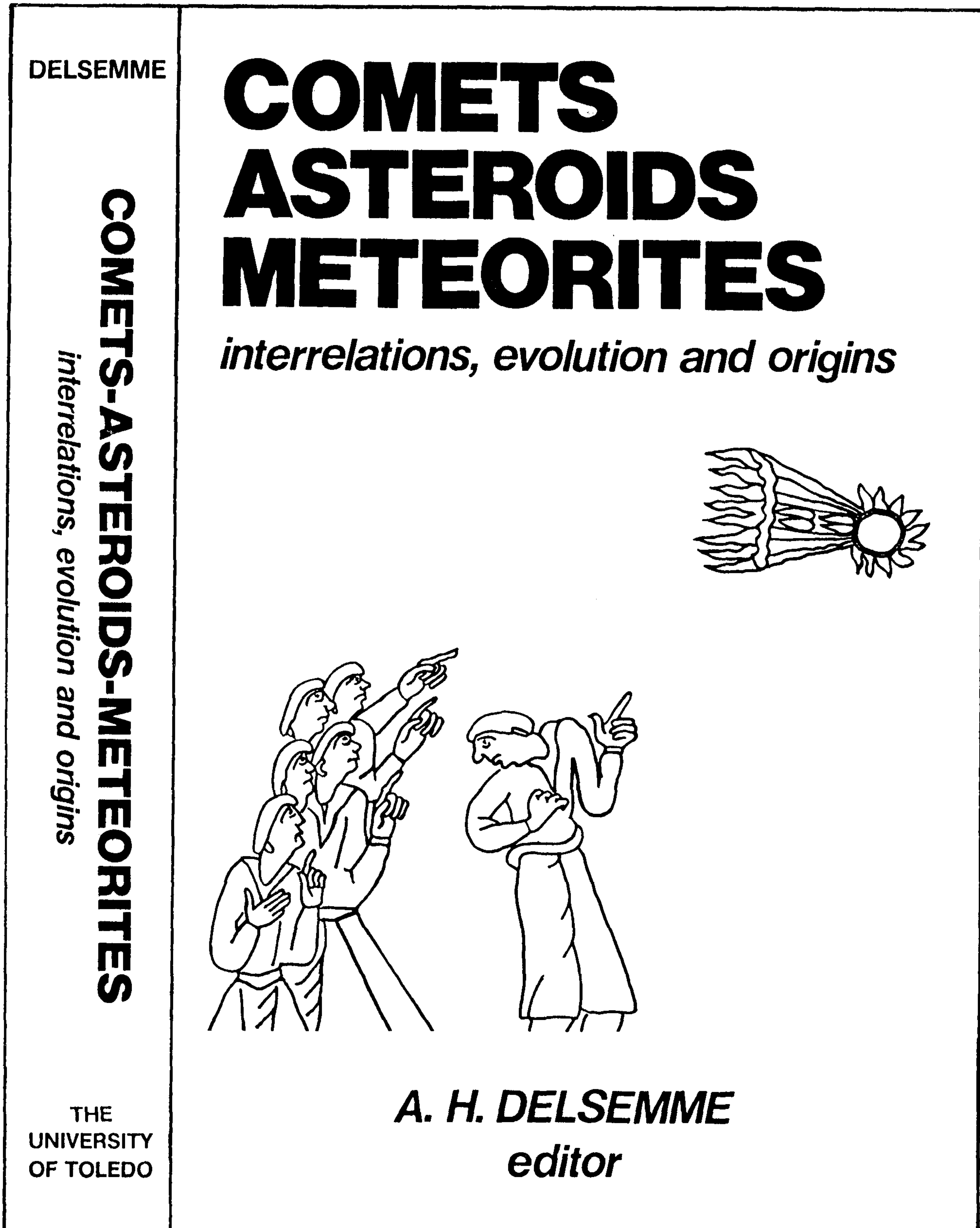


Fig. 8. Sketch of Halley's Comet as shown on the Bayeux tapestry. Used as book cover illustration.

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