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Volume VIII. The Comets

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OVERLEAF: Comets—Remnants of the Primordial Soup?

The abundance and state of constituent materials of comets suggest to many scientists that comets are remnants of the nebular material from which the planets and Sun formed. Some comets are in orbits that have aphelion distances of many thousands of astronomical units. Others have more regular orbits which bring them into the inner solar system with frequencies ranging from once every two or three years to once every two or three centuries.
(Warner and Sawsey Observatory, Case Western Reserve University photograph of Comet Bennett 1970 II, taken with 24–36" Schmidt telescope on April 6, 1970)

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PREFACE

This volume is one of a nine-volume series documenting the work of the NASA-sponsored Terrestrial Bodies Science Working Group in developing plans for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets during the period 1980-1990. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

This volume is the report of the comets subgroup, whose members and contributors are J. C. Brandt (chairman), C. R. Chapman, and F. P. Fanale.

SECTION I

COMETARY SCIENCE OBJECTIVES AND RATIONALE

A. STATE OF KNOWLEDGE

Comets are fascinating bodies displaying a wide variety of physical characteristics; they may be the most primitive remnants of the primeval solar nebula. New comets become observable sporadically and the appearance of most comets changes rapidly with time. The brightest comets are often objects of great public interest.

At the onset, it is imperative that the relatively primitive state of cometary science be recognized. As a result, one cannot easily set out the same level of detailed objectives and plans for cometary exploration as, for example, one might do for Mars and Venus. The present atmosphere is probably not too different from the planning in the late 1950's for the Mariner 2 mission to Venus in 1962.

Cometary science has passed through several stages of development which have led to the present status. Prior to 1970, comets were studied by a rather small number of scientists. Observations were limited to those obtainable from the Earth's surface. Nevertheless, a substantial body of information had been built up; However, major obvious gaps remained. For example, the principal constituents of the cometary nucleus were not known.

In the early 1970's, observations from above the Earth's atmosphere by the Orbiting Astronomical Observatory Copernicus and the 5th Orbiting Geophysical Observatory established the existence of huge clouds of hydrogen and hydroxyl around several comets. These observations (along with others) established that water ice is the principal nuclear constituent, at least for short-period comets. There has been an increase of interest in cometary research in the 1970's, and activity by radio astronomers has established the existence in comets of the exotic molecules HCN and CH_3CN.

The next phase of cometary research, in situ measurement, lies ahead and logically should take place in the 1980's. As a basis for discussion, we outline in the following subsections our basic knowledge of comets.

1. Sizes

The nucleus is commonly held to be a solid body with a radius in the range 1-10 km. It is surrounded by a visual gas-dust coma, which is nearly spherical and is around 10^5 km in radius. Observations from above the Earth's atmosphere have established the existence of a hydrogen-hydroxyl cloud surrounding the coma roughly 10^7 km in radius. Comets can have tails composed of both gas and dust, and the longest can measure up to 2 AU, or approximately 3×10^8 km in length. There is evidence for a halo approximately 10^3 km in radius composed of icy grains.

2. Masses

There are no directly determined masses of comets. However, by assuming a density and determining a nuclear radius, masses in the range 10^{15} to 10^{18} grams have been derived.

3. Composition

The following constituents have been observed in the spectra of comets:

H_2O, OH, CO, CN, CH, C_2, C_3, H, O, NH, NH_2, NH_3, HCN,

CH_3CN, CO^+, OH^+, H_2O^+, CO_2^+, CH^+, N_2^+, Na, Fe, and Ni.

The ions are observed in the tail plasma and the heavy metals are observed in comets when they are very near the Sun.

4. Basic Physics Near the Sun

The predominant constituent of the nucleus of short-period comets is very probably water ice. Minor constituents can be trapped in the crystal (clathrate) lattice, and dust particles can be embedded in the ice as well. Larger solid objects may form a nuclear core. Some long-period comets ("young" in Oort's sense, i.e., most of the comet's lifetime has been spent outside the inner solar system) can apparently have appreciable amounts of a slightly more volatile substance (amounts too large to be contained in the clathrates). The strongest candidates are CO_2 and CO; the latter is attractive because it is a major constituent in interstellar space.

When a comet approaches the Sun, the solar radiant energy causes the nuclear ice to sublime. The gas undergoes transonic flow away from the nucleus and achieves a terminal velocity of approximately 0.3 km/sec. This flow drags the dust particles along to form the gas-dust coma. Small grains of ice are also dragged along and these presumably form the icy grain halo. The dissociation of the water molecules produces the H and OH to form the large hydrogen-hydroxyl cloud.

Comet tails generally point away from the Sun. The dust particles that form dust tails are blown in the antisolar direction by the Sun's radiation pressure and move in an orbit under the Sun's reduced gravitational attraction to form the curved, yellow-appearing tails. Some neutral molecules are ionized and swept into the plasma tail by the action of the solar wind; the plasma is relatively unaffected by solar gravity and forms a normally straight, blue-appearing tail. The plasma tail shows a great deal of filamentary structure which has been interpreted as implying the presence of magnetic fields. These are apparently captured from the solar wind and anchored in the coma region.

5. Orbits

The orbital planes of long-period comets are oriented nearly at random. The long-period comets have orbits that are highly eccentric; i.e., the orbits are nearly parabolic. The short-period comets are believed to have been captured from the population of long-period comets by gravitational perturbation, mostly by Jupiter.

6. Storage

The sublimation of water ice becomes active at heliocentric distances less than approximately 3 AU. For comets beyond this distance and, in particular, at distance $\sim 10^5$ AU taken from the Oort cloud, the comets are normally in superb cold storage. It is also expected that comets undergo essentially no collisions while in storage.

7. Interactions

Comets are definitely responsible for stream meteors. Furthermore, comets are the leading candidates for the source of the dust responsible for the zodiacal light. Finally, comets have a strong interaction with the solar wind. An understanding of comets requires an understanding of the physical processes involved in the comet/solar wind interaction.

B. MAJOR SCIENCE OBJECTIVES

1. The Nature of Comets

Comets are very poorly understood as members of the solar system, and they are valid objects for study in their own right. A basic level of understanding for comets is necessary before we can assert that we understand the solar system and its origin. At present there are no direct measurements of the properties of either cometary nuclei (composition, size) or of cometary magnetic fields. In situ determination of the composition of the nucleus is made easier (and may not require a landing) because comets sublime, sending material accessible to a nearby probe.

Direct missions to comets are needed to finally solve some of the problems referred to above: we must verify whether a solid nucleus exists at all, and if it does exist, we must measure its size. We must measure the magnetic fields in comet tails, and determine the masses of comets. Other measurements needed to test modern theories are the composition of cometary gases and dust as well as the distribution in space of dust, neutral molecules and ionized molecules. All these observations are made difficult by the fact that comets typically change rapidly in time. Thus our measurements require high time resolution.

2. Environmental Investigation

An understanding of the solar wind/comet interaction is necessary for an understanding of comets themselves. As a by-product, we will learn much about plasma physics by studying processes in the comets, in the solar wind, and in the interaction regions. Studies of comets can lead to an understanding of plasma processes which can then be applied throughout astrophysics. In addition, comets remain our best solar wind probes; since their orbits are highly eccentric and oriented nearly at random, they can be used to probe the three-dimensional structure of the solar wind at high ecliptic latitudes currently inaccessible to deep space probes.

The first in-situ measurements of the cometary environment should focus on plasma parameters and magnetic fields. These quantities should be measured as nearly simultaneously as possible in both the solar wind and in the cometary plasma. An additional objective should be to provide direct calibration of comets as probes of the solar wind.

3. History

We have noted previously that before comets make their first excursion into the inner solar system, they have been kept in cold storage without being subjected to collisions. Their low masses imply that internal processes are quite unlikely. Therefore, the cometary nuclei may be the most primitive unaltered debris left over from the solar nebula. An understanding of the structure and composition of cometary nuclei could provide valuable clues to the origin of the solar system.

Crucial information for determining the history of cometary bodies appears to be the exact chemical composition of dust and ices. The first investigation should focus on constituents most likely to be related to long-term history.

4. Relationship to Asteroids and Meteorites

A proper understanding of the smaller bodies in the solar system requires knowledge of the relationships between, for example, comets, asteroids, meteorites, and small planetary satellites. Are these objects part of a continuous distribution? Do they result from the same basic processes of formation, perhaps originating in the early history of the solar system?

The relationships of comets to other small bodies in the solar system will require comparable levels of understanding for comets and the other small bodies involved. When this level has been reached, a synthesis of results will permit studies of interrelationships to begin.

C. PUBLIC INTEREST

Persons involved in cometary research can testify that comets are objects of intense public interest. During the recent apparition of Comet West in March 1976, this interest was easily noted, despite the public's disappointing experience with Comet Kohoutek. An active cometary program would be helpful in providing timely information on comets to the public; it is essential if misinformation is to be minimized. On several mornings in early March 1976, Comet West provided an overwhelming visual spectacle. It was a brilliant triangular object covering roughly 25 x 25 x 15° in the sky. The appearance of other bright comets and the much-heralded apparition of Comet Halley in 1985-86 should whet the public's appetite for scientifically accurate information on comets.

SECTION II

MEASUREMENTS REQUIRED FOR PRINCIPAL SCIENTIFIC OBJECTIVES

Because of the reconnaissance nature of the most probable early missions to comets, we discuss the measurements to be carried out in general terms.

A. NUCLEAR PROPERTIES

The circumstantial evidence for the existence of the nuclear "dirty iceball" is strong, but knowledge of its shape, topography, and possibly even its mass distribution would be very valuable. A first step would be to image the nucleus during a close approach. Detailed studies have shown that a properly designed imaging device would see the nucleus at nominal flyby distances. The so-called "false" nucleus would not be a problem because the requirement is solely one of resolution. Imaging could be done using a stable platform or a spin scan camera.

The composition of the nuclear material is another important unknown to be measured. With a rendezvous mission, a sample might be directly analyzed for atomic and mineralogical composition. If only flybys are possible, the composition would need to be inferred from the material carried into the cometary surroundings by the natural processes which produce the coma and hydrogen/hydroxyl clouds. Dust particles are included in the effluent and these should be analyzed for composition and size distribution.

B. ATMOSPHERIC PROPERTIES

The density and spatial distribution of the major constituents in the atmosphere (i.e., the neutral molecules forming the coma and extended halo) need to be determined as a function of time. This can be done directly (neutral mass spectrometer) or indirectly (spectrometers or photometers). Identification of new molecular species would be an objective of these measurements. Also, the velocities of the major constituents should be measured in order to derive the total mass efflux from the nucleus.

C. PLASMA (TAIL) AND SOLAR WIND INTERACTION PROPERTIES

Direct measurements of ion densities in the tail plasma and of the magnetic fields in the cometary atmosphere and particularly in the tail are required. Devices with sufficiently fast time resolution should be included to measure the properties of plasma waves. If the interaction of the solar wind with the comet involves a bow shock (as widely believed), energetic electrons would probably be produced and these should be measurable with an electron detector.

Measurements in this category have an obvious close relationship with the solar wind plasma surrounding the comet, and suitable measurements should be made to determine the properties of the incident plasma to which the comet responds.

SECTION III

MISSION CONCEPTS AND SCIENCE PAYLOAD

Possible cometary missions range from ballistic flybys to rendezvous. Mission details and experiment complement will depend on the mission flown. We will recommend (see Section V) a priority listing of cometary missions beginning with a Halley's rendezvous. Clearly, this latter mission, if attainable, would provide a magnificent opportunity for in situ cometary measurements and the study of temporal variations. It would be desirable to discuss mission models in terms of a rendezvous mission. Unfortunately, most detailed planning for comet missions has been formulated in terms of ballistic missions and, at present, most available details are in this context.

Therefore, as a vehicle for discussion, we present an approach as given by R. W. Farquhar in his paper "Mission Strategy for Cometary Exploration in the 1980's" and the paper by Farquhar et al. entitled, "Shuttle-Launched MultiComet Mission 1985." The details should be regarded as illustrative only.

A dual spacecraft launch in 1985 could consist of (1) a Halley flyby mission, and (2) a multiple encounter mission to Giacobini-Zinner and Borelly. The launch in March 1985 would consist of two spacecraft carried on a single shuttle vehicle with the schedule given in Table 1.

The high flyby speed for Halley is not ideal, but can be overcome. The best science can be achieved if each flyby consists of two spacecraft: a coma probe and a tail probe. The dual-probe encounter mode is shown in Figure 1.

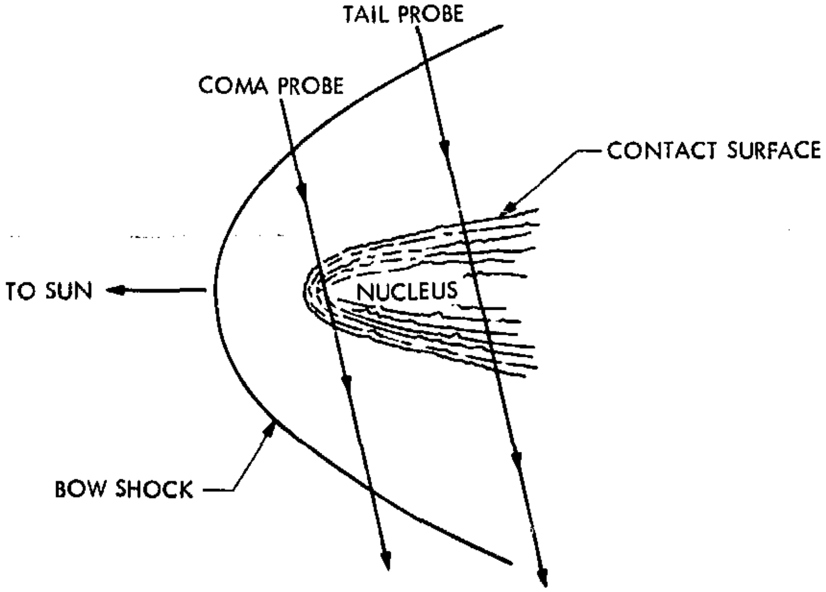

Figure 1. Dual-Probe Encounter Mode

The ballistic mission to these three comets (or even one of them) should provide major advances in cometary physics. Obviously, missions which could achieve a very slow flyby or rendezvous would be even better.

One such possibility utilizes the so-called "solar sail," nominally an area of coated Mylar some 600 meters on a side. Solar radiation pressure is used to drive a spacecraft on a complex, four-year orbit resulting in a rendezvous with Halley's comet near perihelion in early 1986. The sail would probably be discarded as rendezvous was approached. Another option is made possible by recent developments in ion-drive propulsion systems; rendezvous could be achieved this way also. With rendezvous, the spacecraft could station-keep with the comet for an extended period of time and provide an excellent record of the comet's development as it recedes from the Sun after perihelion.

The problem with the solar sail/ion drive mission may be simply stated: the propulsion methods are currently under development (see Volume IX of this report). A launch for a rendezvous in 1986 would have to take place early in 1982. This leaves only 5 years to develop a major propulsion system, which may not be possible within the current fiscal constraints. If the solar sail/ion drive mission were converted to a slow flyby, launch might occur as late as December 1983. Thus, the solar sail/ion drive concept provides us with both a marvelous opportunity and a very serious development problem (see Section V).

Table 1. Cometary Mission Schedule

Spacecraft 1	Giacobini-Zinner	September 1985
	Borrelly	December 1987
Spacecraft 2	Halley	December 1985

Launch Energy and Flyby Speeds

Comet	C_3, km^2/sec^2	Flyby Speed, km/sec
Giacobini-Zinner	12.3	20.6
Borrelly		17.3
Halley	19.2	56.5

Table 2. Cometary Spacecraft Characteristics

- Spin-stabilized with despun platform
- Operating range: 0.80 → 1.40 AU (1.5 → 0.5 solar constants)
- Available power @ 1 AU: 300 watts
- Real-time bit rate @ encounters: 16 kilobits/sec
- Data storage capacity: 3.2×10^8 bits
- Maximum dimensions (launch configuration)

  Length ~ 4.5 meters
  Width ~ 4.0 meters

- Weight summary, kg

Basic spacecraft	380
Tail probe	70
Hydrazine ($\Delta V \sim 300$ m/sec)	80
Experiments	70
	600

Table 3. Typical Experiment Complement

Instrument	Coma Probe		Tail Probe
	Spinning Section	Despun Platform	
Imaging system		X	
Ion mass spectrometer		X	X
Neutral mass spectrometer		X	
UV spectrometer		X	
Lyman-alpha photometer	X		
Magnetometer	X		X
Electron analyzer	X		X
Plasma analyzer	X		
Langmuir probe	X		
Plasma wave detector	X		
Dust detector	X		
Dust composition	X		

SECTION IV

MISSION CONSTRAINTS AND DEVELOPMENT REQUIREMENTS

Major spacecraft or propulsion systems developments are not required for ballistic missions. Clearly, the use of the solar sail or ion drive would require a major development program.

For experiments, a major SRT effort is needed in several areas if successful cometary missions are to be carried out. These areas are:

(1) Ion mass spectrometers. The large range of energies (~0.1 ev to ~1 keV) and the large range of possible masses (1 to 60 amu or more) are difficulties for the usual ion mass spectrometers. Possible solutions are the cycloidal mass spectrometer or several mass spectrometers with different ranges.

(2) Neutral mass spectrometers. The principal problem here is the efficiency of ionization which is ~1% or less with the crossed electron beam approach. Devices using field ionization techniques may be the answer, but additional development is needed.

(3) Dust composition devices. Analysis of dust composition is very difficult but very important. The dust particles first need to be vaporized and then analyzed by means of a mass spectrometer.

A major mission constraint will impact the orderly development of the direct exploration of comets. A complete program would include the probing of at least one of the very large comets which produce the entire gamut of cometary phenomena. Only one such comet has a known, predictable orbit and this is Halley's comet. Thus, the era of the 1980's is urgently unique.

SECTION V

CONCLUSION AND RECOMMENDATION

A well-planned mission to one or more comets in the 1980's is essential to the development of cometary physics and the understanding of the solar system as a whole. It is simply not possible to claim that we understand the solar system if objects with atmospheres larger than the Sun and tails around 1 AU in length are wandering about without being understood. At present, comets can easily claim the distinction of being the least understood of all the objects currently under our review. Therefore, we conclude that the maximum mission to the maximum comet -- solar sail or ion drive rendezvous to Halley -- should be carried out. However, if this mission should not be possible, it is imperative to recognize that any of the ballistic missions to Halley's comet or to several other comets currently being considered would provide a very major advance in cometary and solar system science. The opportunity for _in-situ_ studies of some kind on Halley's comet must not be allowed to escape.

Therefore, we recommend the following priority for direct cometary exploration in the 1980's:

(1) The solar sail/ion drive mission to Halley's comet launched in 1982 to rendezvous with the comet near perihelion in 1986.

or

(2) The solar sail/ion drive mission to Halley's comet launched in approximately December 1983 for a slow flyby.

or

(3) A ballistic mission to Halley's comet.

or

(4) A ballistic mission to other comets such as Giacobini-Zinner and Borrelly.

In view of the uncertainty in the solar sail/ion drive development, we recommend that both a solar sail/ion drive mission to Halley's comet and a ballistic mission to Halley's comet and several other comets be given agency approval for study, planning, and development at least to the point where the best option can be chosen.

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