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Technical Memorandum 33-297

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Preface

This document describes several possible scientific objectives with their supporting experiments and also provides the scientific information for a preliminary study of a comet mission to be launched during the period from 1970 through 1976. It was prepared as a joint effort by the Future Projects Office and the Space Sciences Division of the Jet Propulsion Laboratory.

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Abstract

Several possible scientific objectives for a comet mission, with their supporting experiments, are described. Background scientific information is also provided. An *Atlas/Centaur* launch vehicle is assumed, as is also a spacecraft–comet encounter, with a miss distance of less than 2500 km. A select list of scientific experiments on board an intercept probe of this type can be expected to provide data towards a major advance in our understanding of comets. It is the thesis of this report that a space-probe to a comet may be potentially the most important mission for purposes of cosmogonical research that will be within the capabilities of the early 1970's.

Mission to a Comet: Preliminary Scientific Objectives and Experiments for Use in Advanced Mission Studies

I. Introduction

In the days before city lights and smog, the average man would be treated to the view of a spectacular comet, easily visible to the naked eye, several times during his life. In 1965, the comet Ikeya-Seki put on the most spectacular display since the 1910 and 1927 daylight comets, yet it was seen only by those willing to make a trip out of the city before sunrise. Though comets may be becoming unknown to the city dweller, the scientist is finally acquiring the tools to solve many of the problems concerning comets that have puzzled him for centuries. This document is concerned with the need for application to comets of the most modern tool of all, the space probe.

When first observed, far from the Sun, a comet appears as a fuzzy area of light. As it plunges into the inner parts of the solar system, it may appear to change in size and it usually develops one or more extensive tails which may trail out from the comet to a length of more than 100 million kilometers. The most spectacular comets are possibly new comets or those from far out in the solar system, which have not been subjected to repeated solar passages. It is obvious that material is being used up, or "boiled off," in each passage near the Sun.

The nature of the observational information on comets has led to many theories and a great deal of speculation about these solar system wonders. Perhaps comets are formed originally from interstellar dust, and thus may provide an accessible sample of interstellar material, or perhaps they represent a sample of the original solar-system condensate. Knowledge of the chemical composition of the material in a comet is certainly desirable, for it could represent a better estimate of the composition of primordial matter than anything else, and lead to important conclusions about the origin of the elements.

Perhaps a comet is formed as a giant snowball or even a diffuse swarm of particles. What would be the effect of a cometary impact on a planetary atmosphere or surface? Could the large lunar craters and other lunar surface features be the scars of such encounters?

If we understand anything about comets, it is that they are very different from the Earth and may be among the most interesting scientific bodies in our solar system. Because comets are so little understood, and because of the diversity of speculations about them, the selection of suitable and acceptable scientific objectives and experiments for a comet-intercept mission is not an easy task, and, further, it is one that must be subjected to review by a large segment, comprising many disciplines, of the scientific community.

II. Mission Constraints

In order to derive the maximum scientific value from a comet-intercept probe, it is necessary to define several mission constraints that affect not only the choice of experiments and their unique requirements and techniques for implementation, but also the feasibility of the mission itself. These comet-mission constraints, as presently conceived, are discussed in this section.

The selection of a specific comet for an intercept mission will not be attempted in this document. This can be accomplished only after a detailed analysis has traded off the constraints listed below as applied to particular comets, with technical data involving constraints on the launch vehicle, launch window, flight time, approach velocity, communication distance, guidance and control, and, finally, the mission's scientific objectives and their resulting scientific instruments.

A. Launch Vehicle Capability

The launch vehicle assumed for this study has at least the capabilities of an *Atlas/Centaur*. Because of the high injection-energy requirements for most comet missions, and the relatively modest capability of the *Atlas/Centaur* launch vehicle, target selection is limited, as also are spacecraft weight and the resulting scientific payload. Even so, preliminary trajectory analyses indicate that there will be several favorable comet apparitions for the time period of 1970 through 1976 that are amenable to study from a lightweight *Mariner*-type spacecraft. These opportunities are expected to allow the consideration of 110 to 150 pounds of scientific payload for a particular mission. This is certainly adequate, and a select group of scientific experiments on board an intercept probe of this type can be expected to provide data towards a major advance in our understanding of comets.

B. Intercept Miss Distance

A spacecraft–comet encounter miss distance of less than 2500 km from some preselected part of the comet is desirable. Through Deep Space Instrumentation Facility tracking and programmed trajectory corrections, the spacecraft's location in space will be both known and, within limits, capable of some adjustment; however, the comet's trajectory will be less well known, and so the precise point and time of spacecraft–comet encounter will be largely dependent upon knowledge of the cometary orbital elements. This suggests that an extensive accompanying optical observation program of the comet will be necessary throughout the apparition—that is, possibly for several weeks prior to spacecraft launch and also during the flight portion of the mission. This further suggests that the selection of any particular comet for the mission should be limited to those short-period ones whose orbital elements are already reasonably well known and whose apparition can be predicted to be bright enough to permit early recovery.

Previous studies (Ref. 1) of the trajectories, orbital determination techniques, and spacecraft guidance problems for a number of selected comet missions have indicated that the requisite 2500-km spacecraft–comet encounter miss distance is feasible. This would be without the complication of an on-board comet seeker for in-flight and terminal guidance. The general comet selection and guidance procedure for achieving this accuracy in flyby distance is envisioned as follows:

(1) Use the data from earlier apparitions of a number of selected short-period comets to determine their orbits, predict intercept points, etc., and select the most suitable one as a likely target.

(2) Begin optical tracking of the comet from several facilities at its first appearance to determine a more precise orbit and intercept point. It is possible that this phase could begin some months before launch.

(3) Launch the spacecraft on the basis of (2) above.

(4) Track the spacecraft and the comet.

(5) Use midcourse and terminal corrections to achieve final rendezvous.

C. Desirability of Intercept Close to Perihelion

Except for the rare annual comets such as Schwassmann–Wachmann 1 and Oterma, comets usually become visible only as they approach the Sun and become subject to increasing solar radiation. Their most active period is near perihelion; therefore, it is desirable to have the spacecraft–comet intercept occur at or near perihelion passage. This is also an important consideration for the constraint discussed in the following section.

D. Visibility From Earth During Intercept

This places a requirement on both the brightness of the comet and its trajectory. It is very desirable that the comet be visible from Earth during the intercept phase to allow the correlation between data from the spacecraft scientific instruments and data from Earth observatories, and perhaps, by then, even orbiter observation. Thus, any comet chosen for this mission should be a visual comet, or, at the least, one that is capable of achieving a brightness magnitude of at least 10 during the intercept phase of the mission; this is especially desirable for carrying out any Earth-based spectroscopic observations. This constraint is a difficult one, as few periodic comets have been observed to brighten up to visual magnitude as high as 6^m.

E. Closing Velocity

Closing velocities determine how long the spacecraft will be in a particular comet and also affect the design of the scientific instruments, their data rate, and the scan platform. In most cases, the comet overtakes the spacecraft. A low closing velocity is desirable, with the comet flying slowly by the spacecraft; however, a differential velocity of up to 15 km/sec would be acceptable.

F. Trajectory Constraints for Approach, Fly-Through, and Recession From the Comet

It is desirable to fly through the coma and as close to the nucleus as possible in order to observe the central core of the comet. The desired trajectory is expected to pass through the coma, and as discussed earlier, to within 2500 km of the nucleus. Further, the trajectory should offer an opportunity to perform scientific experiments on the comet's coma and tail during the approach and recession portion of the flight. It should be noted that, for most trajectories, the cometary tail cannot be intercepted on leaving the coma without a significant change in the course of the spacecraft. Additional trajectory constraints that may be desirable for specific scientific experiments are discussed in Section III.

G. Spacecraft Hazard

The physical state and distribution of matter within a comet are largely unknown; thus, the actual coma penetration phase of this mission could involve a hazard to the spacecraft. For this reason, it may be desirable to have certain critical spacecraft components shielded and also to have a real-time or at least a high-data-rate transmission capability for monitoring the spacecraft's engineering and scientific data. In this way, it may be possible to have information of a hazardous situation before loss of contact with the spacecraft. Fortunately, the intercept phases of most of the comet missions that are practicable seem to occur when the communication distance is very small—say a few tenths of an AU. This could be an important advantage in sizing a communication link for high-data-rate transmission.

III. Comets: Observation and Theory

A. General

The word "comet" comes from the Greek word "kometes," meaning long-haired, an appropriate appellation for the long-tailed objects generally visible to the naked eye. Because of their apparently random times of appearance, spectacular nature, and relative rarity, comets have often been objects of terror among the superstitious. Many early scientists thought them some sort of atmospheric phenomena. At the beginning of the eighteenth century, Halley successfully applied the new gravitational theory of his friend Newton to the comet problem and proved comets to be well-behaved members of the solar family, although traveling in highly elongated orbits.

A few comments on nomenclature are needed. Each comet, in order of discovery or recovery in a given calendar year, is provisionally designated by that year and a letter of the alphabet; thus 1966a, 1966b, 1966c, etc. Several years later, after their orbits are determined, comets are finally redesignated with the year and a roman numeral in the order of their perihelion passage; thus 1958 I, 1958 II, 1958 III, etc. By this time any mistaken claims will have been discarded. Each comet is also designated by the name of its discoverer or discoverers, not to exceed three names; thus 1965f Ikeya-Seki and 1957 V Mrkos. If the comet is found to be periodic, it is usually preceded by P/; thus P/Halley and P/Encke. It may often be preceded by its most recent observed perihelion passage designation, such as 1910 II P/Halley. If the discoverer has more than one comet to his credit, the name is followed by a number; thus P/Tempel 1 and P/Tempel 2. In a few cases where a comet has been lost for several returns, the name of its recoverer is sometimes added. Thus P/Perrine, recovered by Mrkos in 1955 after being lost for six returns (40 years), is now P/Perrine-Mrkos. There are a few cases where the name of the computer has been given to a comet, the most notable being P/Halley. Halley, of course, did not discover the comet named after him but rather proved that the brilliant comet of 1682 was the same as that of 1607 and 1531 and successfully predicted its reappearance in 1759.

B. Orbital Characteristics

The things most precisely known about comets are their orbital elements, although even here the uncertainty is far larger than for planetary orbits. Comets can be roughly divided into two classes, the "short-period" or just "periodic" comets having periods up to 200 years, with about a hundred members currently known, and the "long-period" family with periods averaging 50,000 years or more and numbering possibly on the order of 10^6 to 10^{12} members.

A further distinction can perhaps be made among the "long-period" comets by distinguishing their orbits as hyperbolic or nonhyperbolic. It has been an important scientific question whether or not hyperbolic comets, entering from interstellar space and never before attached to the Sun, do indeed exist. But it is now universally recognized that *many* comets having hyperbolic orbits when moving near the Sun were perturbed into those orbits from their former elliptical paths by the action of one or more of the planets, usually Jupiter. Such comets then are lost to the solar system for all future time.

The outstanding cometary orbit authority J. G. Porter makes the definite statement that "*all* comets are members of the solar system" and that "a comet may escape from the solar system, but it did not enter it from interstellar space" (Ref. 2). Z. Sekanina, on the other hand, states that "at present 5 hyperbolas are known almost beyond doubt, 5 comets are under strong suspicion of having hyperbolic original orbits and 9 comets are under weak suspicion" (Ref. 3).

Richter (Ref. 4) gives the following statistics of cometary apparitions up to September 1962 for which orbital elements have been computed. The list includes 843 orbits of 571 individual comets.

Short-period comets:
327 appearances of 55 short-period comets
39 short-period comets seen only once to date

Long-period comets:
121 long-period elliptic comets
289 parabolic comets
67 "hyperbolic" comets

As already noted, most or all of these "hyperbolic" comets were not hyperbolic until perturbed just before the period of observation. The parabolic comets are not truly parabolic (eccentricity exactly 1) but are rather just comets whose observed positions can be adequately satisfied by a parabola to within the limits of accuracy of the observations. Preliminary orbital calculations for comets are usually based upon the assumption of a parabola, since most previously unknown comets will exhibit an eccentricity of more than 0.99.

Long-period comets are not completely randomly distributed. The number within a given inclination is roughly proportional to the sine of the inclination with a deficiency from 100–120 deg and an excess from 120–150 deg. Their nodes are roughly uniform in distribution, but the distribution of aphelia, a measure of the direction from which comets have come, is nonuniform, there being numerous concentrations and several regions showing no comets (Ref. 5). There are definite groups of long-period comets having almost the same orbital elements except for the time of perihelion passage. The famous Sun-grazers, of which Ikeya-Seki (1965f) is the most recent of seven known members, is such a group. These groups tend to cause a clumpiness in the distribution of aphelion points.

The periodic comets are anything but randomly organized. More than two-thirds of the known examples have inclinations less than 20 deg. Only seven out of the total of 94 are in retrograde orbits as opposed to about half of the long-period objects. The aphelia of 67 of the 94 periodic comets lie between 4 and 8 AU from the Sun, with 52 of them between 4 and 6 AU. These 67 comets are usually referred to as Jupiter's comet family. Russell (Ref. 6) and Strömgren (Ref. 7) have shown conclusively that the action of Jupiter has indeed greatly changed their orbits, in effect capturing them from long-period orbits. In fact, Jupiter has played a major role in the determination of the orbits of most if not all of the short-period comets. Even Halley's comet, with an aphelion distance of 35.3 AU, can at present come no nearer than 8 AU to the orbit of Neptune but can come within 1 AU of that of Jupiter (Ref. 2). The other major planets have had measurable effects upon various comets, of course, but there is no good evidence that any of them have comet families (Ref. 2). In fact, a study of cometary nodal distances (the distances from the Sun at which a comet crosses the ecliptic plane) indicates that Jupiter and possibly the terrestrial planets Venus, Earth, and Mars are the chief cometary perturbers.

The changes effected in the orbits of periodic comets by Jupiter are not small. For example, from 1858 to 1964, Jupiter's interaction with P/Pons-Winnecke changed the comet's period from 5.56 to 6.30 years, its perihelion distance from 0.77 to 1.23 AU, its eccentricity from 0.755 to 0.639, and its inclination from 10.8 to 22.3 deg (Ref. 4). In 1886, P/Brooks 2 passed within two Jovian radii of Jupiter, and its period was changed from 31 to 7 years in the one interaction (Ref. 4). P/Oterma had a period of 18.0 years in 1934, 7.9 years in 1950, and 19.2 years in 1965.

Comets of the Jupiter family cannot be differentiated from minor planets (asteroids) on the basis of orbit alone. Roemer has remarked that "When I observed Comet Arend-Rigaux on its last apparition I found that it was completely stellar on all plates. The orbit is similar to that of a minor planet, but the object was designated as a comet because it on occasion showed some diffuseness. When Baade discovered Hidalgo he was undecided whether to call it a minor planet or a comet, but he decided on the former simply because more people were observing minor planets at the time and it would be better taken care of!" (Ref.8).

Actually, there are only some twenty-odd asteroids out of 1600 with eccentricities greater than 0.35 that move in paths similar to those of the periodic comets, and these similarities should *not* be over-emphasized in attempts to read cosmogonic significance into them. The probable explanation is that two classes of bodies, comets and asteroids, each of relatively low mass, are at times subject to similar perturbing forces with resulting similar consequences, although this has not been proved and a closer relationship is conceivable.

A final subject of some importance is that of the secular acceleration of comets. It has been widely stated that a number of comets have exhibited a secular acceleration in their mean motion, the largest quoted being that for Encke's comet of 43×10^{-6} sec of arc/day (Ref. 9). Indeed, the original icy conglomerate model was proposed by Whipple largely to explain this acceleration and a few other features difficult to explain on the basis of a "sandbank" model (Refs. 8, 10). Roemer has questioned the reality of the acceleration, suggesting the possibility that residual observational errors are more than sufficient to account for the apparent effect (Ref. 8). Resolution of the problem will have to wait at least until additional perihelion passages of some of the comets of shortest period are accumulated.

C. Observed Structure

*1. **Nucleus.*** A comet consists of a nucleus, a coma, and usually one or more tails. The nucleus and coma together are called the head. The nucleus is the name given to the starlike point of light appearing at times within the coma. It requires a fairly large telescope and long focal length even to see the nucleus of most comets, and photography is also difficult due to the lack of contrast against the coma. Roemer has possibly had the most experience of any modern astronomer in this area, and she states "It is our experience that the overwhelming majority of comets have essentially starlike nuclei that can be observed photographically with the 40 inch, f/6.8 Ritchey-Chretien reflector, but that these nuclei almost invariably are fainter than magnitude 13 or 14 regardless of the total brightness of the comet" (Ref. 11). Roemer feels it likely that the nucleus is a small solid body. Richter stated that "the term nucleus can be understood to refer to the optical center of the comet, and we can speak of the photometric nucleus" (Ref. 12). He notes that not *all* comets show *anything* that could be called a nucleus, not even a central condensation, let alone a starlike nucleus, while some show a condensation resembling a planetary disc or several discs (Ref. 12). The weight of observational evidence seems to be with Roemer that such difficulties are due to inadequate apertures used by many observers.

In cases where a starlike cometary nucleus has existed of sufficient brightness to attempt slit spectroscopy, the result has been a Fraunhofer spectrum of reflected sunlight, with only a few weak gaseous emission lines superimposed (Ref. 12), and these emission lines may well be from the surrounding coma. Photometrically the *nucleus* seems to follow an inverse square law rather well, again what would be expected of a body shining by reflected radiation (Ref. 12). Assuming the nucleus is a compact body following Lambert's law of reflection, a radius may be calculated for any assumed albedo. Typical periodic comets show nuclear radii from 0.1 to 2 km, assuming an extremely high albedo of 0.70, and 1 to 10 km, assuming an opposite extreme albedo of 0.02 (Ref. 13). If these values are typical of nuclear radii, it is obvious why small telescopes see so little and why even large ones still do not resolve a disk. For nearly parabolic comets, radii are typically twice as great, while exceptional objects in both categories may be 5–10 times larger (Ref. 13). Assuming a middle value for the albedo (0.25) and a mean density of 3 g cm^{-3}, nuclear masses would typically lie in the range of 10^{17}–10^{20} g with a few exceptional objects going as high as perhaps 3×10^{22} g. Whipple has turned the problem around and attempted to build a "new" Halley's comet from estimates of dust and gas loss by the comet at each perihelion passage. He finds a minimum total mass of 10^{17}–10^{19} g (Ref. 14). No cometary mass has ever been measured gravitationally and two comets have been observed to pass within the Jovian satellite system without causing measurable effect upon the satellites. This is consistent with the masses discussed above.

If the comet is not a compact body but rather a gravitationally associated cloud of dust, the masses are roughly the same while the dimensions are one to several orders of magnitude larger (Ref. 12). According to Lyttleton, the masses are again comparable to those discussed above, but there is no real nucleus (Ref. 15).

2. *Coma.* The head of a comet is quite large and very tenuous. Just how large is difficult to state, since the apparent size varies with the aperture, focal ratio, and detector used for the observation, as well as with the distance of the comet from the Sun. A typical diameter is 10^5 km, although many cases of 10^6 km have been measured, and 6×10^6 km is claimed for 1943 I (Ref. 16). Star trails can usually be photographed right through at least the outer parts of the coma. In some cases the coma appears to shrink in size as the comet approaches the Sun, while in others it may grow (Ref. 12). The coma is roughly spherical in shape and the nucleus is more or less at its center. This would seem to indicate an isotropic streaming of material from the nucleus (assuming the nucleus exists).

The spectrum of the head (coma) of a comet near perihelion consists most prominently of emission bands of CN and C_2. Other neutral molecules that have been identified are C_3, OH, NH_2, NH, and CH (Ref. 17). Forbidden lines of atomic oxygen were first identified by Swings and Greenstein in 1958. Atomic sodium is often identified in comets that closely approach the Sun (nearer than 0.7 AU) (Ref. 17). High-dispersion observations of the recent Sun-grazer Ikeya-Seki (1965f) confirmed an earlier visual observation of atomic iron and definitely added Ca I and Ca II while suggesting H, Sr II, Fe II, and Mg I in increasing order of doubt (Ref. 18). Several other workers obtained spectra of 1965f, and new information may soon be published. Ionized molecules are characteristic of the tail, but CO^+, N_2^+, CO_2^+, CH^+, and possibly OH^+ all may appear in the region of the head (Ref. 17). It is difficult to disentangle the head from the initial part of the tail where it leaves the comet. The head usually also exhibits a weak continuum of reflected sunlight, indicating the existence of scattering or reflecting particles (Ref. 16). The continuum seems in some cases to be slightly reddened (Ref. 17).

It is difficult to get any accurate quantitative measure of abundances in the coma, for many reasons. Abundances vary from comet to comet and they vary within the coma, and the relevant atomic constants and mechanisms are not perfectly known. However, Wurm estimates for a typical bright comet such as Halley's that the C_2 density will be roughly

$$\rho(C_2) = 10^{21.5}\, r^{-2} \text{ molecules/cm}^3$$

where r is the distance from the center of the nucleus in centimeters (Ref. 17). At 10^5 km from the origin, the density will be down to $10^{1.5}$ C_2 molecules/cm^3. The value for the CN molecule is slightly greater (Ref. 17), while NH and OH are not much different (Ref. 16). The density of C_3 would be somewhat less, perhaps by a factor of 30. The density of CO^+ was 30 times as great as CN in 1948 I (Comet Bester) at a distance of 130,000 km from the nucleus in the direction of the tail (Ref. 17). Sodium has such a large transition probability for its resonance lines that it is highly accelerated by light pressure and appears to form a paraboloid rather than a sphere around the nucleus (Ref. 16).

All gas production is a strong function of heliocentric distance. Beyond 3 AU, only a continuum is normally observed. As the comet comes inward, a coma begins to develop and CN emission appears, followed at about 2 AU by NH_2 and at 1.7 AU by C_3. These show a smaller monochromatic image than pictures taken in CN light. The Swan bands of C_2 appear clearly at 1.8 AU (Ref. 17). The comments on abundances in the previous paragraph refer to a well-developed comet at perhaps 1 AU from the Sun.

It is difficult to get any estimate of dust-particle mass or density in the coma. Some comet heads contain a great deal of dust as shown by rather strong spectral continua, others virtually no dust. There is not even a direct correlation between dust in the coma and so-called dust tails, since the dust particles must be just the right size for light-pressure acceleration to form a proper dust tail (Ref. 16). Vanýsek has attempted an estimate of dust in the coma from the continuum strength, assuming properties for the dust grains, and finds the total mass varies from about 3×10^7 g for P/Encke to almost 10^{12} g for objects such as Arend-Roland (Ref. 19). The coma of Arend-Roland was some 3×10^5 km in radius (Ref. 20).

This implies a *mean* density of 10^{-20} g/cm^3. Assuming the particles to be a micron in diameter (Ref. 21) and with a density of 3 g/cm^3, they would have a mass of about $3/2 \times 10^{-12}$ g/particle and there would be about 7×10^{-3} particles/m^3. Assuming an inverse square density increase toward the nucleus, this would imply 70 particles/m^3 at a distance of 1500 km from the center of the nucleus. The particle density would be considerably lower in a comet such as P/Encke, which is nearly as large but has much less dust. It must be recognized that these figures depend strongly on assumptions and could easily be off by orders of magnitude.

The photometric behavior of the coma differs greatly from the nucleus (which follows a routine inverse square brightness with distance from the Sun). Values have been measured all the way from inverse 11.4 power to direct 1.77 power, although comets with inverse values greater than two are in the great majority (Ref. 12). Most of the visible light from the coma is the result of fluorescence excitation of gases by the Sun, and the brightness of a comet must be, among other things, a function of the number of molecules of gas available for excitation and the efficiency of the detailed mechanism. These processes are not well understood. Some additional discussion is included in the section on the nature of comets.

*3. **Tail.*** The spectacular visual glory of a great comet is its gigantic tail. P/Halley showed a tail at least 3×10^7 km long in 1910. That of Arend-Roland was 5×10^7 km in length, and the great comet of 1843 showed a tail 32×10^7 km long (Ref. 12). These tails may be 10^6 km in width (Ref. 12). Yet some faint comets never develop an appreciable tail, simply appearing as a small diffuse cloud. Other comets may develop more than one tail, and tails of the same or different comets may differ greatly in appearance and behavior at different times.

In 1903, Bredikhin developed in considerable detail a complete mechanical theory of cometary tails previously begun by Bessel (Ref. 17). This theory assumed that once particles received an initial velocity from the comet nucleus they moved strictly in a field of attraction force due to the Sun and the repulsive force of solar radiation pressure. If the repulsive force was strongly dominant, they were rapidly accelerated back from the nucleus virtually in a straight line away from the Sun. Such straight narrow tails were called Type I. If the repulsive force was weak the tails were strongly curved and called Type II. A related weak acceleration tail called Type III was due to an outburst of particles with a small range of weak acceleration (as opposed to the usual continuous emissions of particles) which resulted in a nearly straight tail (Ref. 22).

Comet tails generally lie in the plane of the comet's orbit. Unless the Earth is reasonably far out of that plane it may be difficult to observe just how the tail is behaving. Tail spectra characteristically show emission due to CO^+, N_2^+, CO_2^+, CH^+, and OH^+ and may show a continuum (Ref. 17). It is usual to place CN in the tail also (Ref. 12), but Wurm would deny this (Ref. 23). When the Earth is far enough out of the plane of a comet's orbit, it is seen that the comet may have a pure ion tail that appears to be Bredikhin's Type I, a pure dust tail of Type II (or III), or both (Ref. 17). In fact, it can appear to have several tails. Any tail appearing to contain both ions and dust more than a few million kilometers from the nucleus is just a projection effect of one tail on top of the other. The accelerations in the ion tails are far greater than can be given to dust particles, and the dust particles show no ability to generate gas (Ref. 16). They are either completely degassed before they leave the coma or never had any significant amount of gas in them (Ref. 16).

The accelerations in ion tails are very high, typically showing repulsive forces 35 to perhaps 200 times the attractive force of solar gravity (Ref. 17). The oscillator strengths of molecular tail gases are quite small, and such accelerations are absolutely impossible to attribute to radiation pressure by a factor 10^2 or 10^3 (Ref. 17). This statement obviously does not apply to atomic sodium with its resonance D lines. Biermann was the first to investigate the effects of solar *corpuscular* radiation upon ion tails (Ref. 24). At first the forces seemed great enough, and for a few years it was felt that only the details needed to be worked out. With the advent of the space program, however, corpuscular densities in interplanetary space were accurately measured for the first time and were found to be much too low to cause the observed tails via a straight collisional interaction, although the individual particle energies are high (Ref. 17). The interaction is apparently a much more complex magnetohydrodynamic one than originally thought and is the subject of much investigation today (Refs. 25, 26, and 27).

Until recently, it was generally felt that the classical theory of Bredikhin was adequate for the dust tails (Ref. 24); however, Belton has suggested that some features of dust tails are unexplained by this theory and that the dust particles are probably charged and, with accompanying electrons, form a plasma (Ref. 28). This turns the nature of the dust-tail mechanism into a rather complex problem. Levin has even suggested that the evidence that Type II tails exhibit nothing but a continuum is not really so good, and that in fact the Type II tails are really primarily neutral gas tails (plus some dust) (Ref. 22). Levin still pictures the Type III tail as a pure dust structure, following Bredikhin's theory.

Densities and mass losses in tails are quite difficult to estimate. Liller found the total tail mass of 1957 III Arend-Roland and 1957 V Mrkos to be 10^{13}–10^{14} g, and found mass losses of 5×10^{14} and 7×10^{15} g per revolution respectively (Ref. 21). Assuming the particles in these dust tails to be iron spheres, his measurements indicated they must be about 0.6 μ in diameter with individual masses of 8×10^{-13} g. Wurm points out that the brightness of Arend-Roland would be consistent with such particles if they had a mean separation of 4.2 m (Ref. 17). Wurm also notes work by Vanýsek that arrived at tail masses of 10^{11}–10^{12} g and mean densities of 10^{-18} g/cm^3 for the average brighter comet tail (Ref. 17).

The density of gas in a Type I tail is also difficult to estimate. It is not so much a question of abundances of what can be seen as it is a question of what is there that cannot ordinarily be seen. For Halley's comet, a half degree back from the nucleus the CO^+ density in 1910 was about 300 molecules/cm^3, requiring a production rate of about 10^{28} molecules/sec to maintain the steady state (Ref. 17). In general, it might be expected that CN would be 30 times less abundant, say 10 molecules/cm^3, C_2 having 5 molecules/cm^3, C_3 having 0.2 molecules/cm^3, with NH and OH being similar to C_2. These values apply to a distance of some 175,000 km from the nucleus, really still in the head, of a relatively bright comet. Moving on back in the tail, one would expect the neutrals to continue to drop in density roughly inversely as the square of their distance from the nucleus. The CO^+ ions, however, are driven back very rapidly in a narrow Type I tail and presumably fall off in density very slowly. The N_2^+ behaves similarly to CO^+. The other ions, CO_2^+, NH^+, and OH^+, are so weak that they are seen only near the head and their behavior is not known. Further, it is suspected that undetected ions such as HCO^+, H_3O^+, H_3^+, etc., may be present in large quantities (Ref. 25).

The production of all comet tails is a strong function of heliocentric distance, tails usually being produced at distances less than 1.5 AU (Ref. 17). The intensity of ion tails is even more strongly distance-sensitive than that of dust tails. Exceptional comets have produced tails at distances much greater than 1.5 AU, 1908 III Comet Morehouse producing a CO^+ tail more than 2 AU from the Sun (Ref. 17).

D. Theoretical Structure (Cometary Models)

Cometary models generally fall into two classes, the particulate or "sandbank" models and the compact models, the most notable of which is Whipple's icy conglomerate model. None of the models is completely satisfactory, but they offer insight into the problems of understanding comets, and above all suggest what experiments may be crucial to ascertaining the true nature of comets.

For almost a century the most prevalent view was that a comet consisted of a large number of solid particles of varying sizes possessing some gravitational coherence and in orbit about the Sun—the sandbank model. In 1953, Lyttleton presented details of a comet model in which gravitational coherence could operate only at great distance from the Sun, while at planetary distances each particle would be in its own independent Keplerian orbit about the Sun (Ref. 15). On the basis of this model, most periodic comets would have negligible self-attraction as compared with the solar action. Lyttleton suggests that collisions occur near perihelion between independent particles in the comet, owing to the orbital crossings on the perihelion side of the latus rectum of the mean orbit. These collisions would shatter particles, offering fresh surfaces for desorption, and would perhaps effect direct gas production through intense local heating (Ref. 29). Even if this mechanism produces sufficient gas, which remains to be proved, the average comet begins to produce gas at a heliocentric distance of 2.5 to 3 AU, which in many cases is long before it crosses the latus rectum.

The idea that condensed or condensable gases might be present in comets goes back before the beginning of the present century. However, until something of the composition and quantity of gases and dust present in comets was obtained and until certain other factors, such as the secular acceleration, appeared to be well established, there was no reason to be overly suspicious of the sandbank theories. In 1950 Whipple proposed his icy conglomerate model, a model in which the nucleus was visualized "as a conglomerate of ices, such as H_2O, NH_3, CH_4, CO_2 or CO, (C_2N_2?), and other possible materials volatile at room temperature, combined in a conglomerate with meteoric material" (Ref. 10). The description was expanded in later papers (Refs. 30–33), and many other researchers have since made contributions.

It was soon pointed out by Delsemme and Swings that the sublimation rates in a vacuum were all wrong for such substances as CH_4, NH_3, and H_2O to be subliming simultaneously (Ref. 34). Yet that was what had appeared to be required to obtain the spectroscopically observed daughter products. Delsemme and Swings suggested instead that the substances present were hydrates such as $CH_4 \cdot 6H_2O$. Various authors have since confirmed that if there are CH_4, NH_3, CO_2, etc., present in a comet, they must be present as such hydrates (in fact, probably as mixed hydrates) to satisfy thermodynamics (Ref. 35). (The vapor pressure of CH_4 in such a hydrate is decreased by 10^3 to 10^6, for example.) There are now no conflicts with spectroscopic abundances of neutral molecules.

An interesting observation is that old comets, comets that have short periods and have been around the Sun many times, show primarily gas spectra, whereas new comets show continua due to dust. This is just the opposite of what might be expected of a sandbank comet releasing absorbed gas. This adds structure to the icy conglomerate model, suggesting that meteoric material near the centers of old comets begins to adhere, making available dust rare, while fine unconsolidated dust predominates near the surface of new comets or very small comets (Ref. 14). The possibility of cohering carbon dust at the center of comets also exists (Ref. 14).

More elaborate models are now being built from Whipple's original concept, such as Delsemme's "dirty snowball." Delsemme (Ref. 36) stated

> "We visualize the homogeneous crust of our model as made by an open structure of small crystals in needles linked by filamentary bridges. In short it is snow rather than ice. These crystals are pure water on the outside surface; CH_4 and NH_3 escape by molecular flow through all the small channels between the snow needles and come from levels of known temperatures, whose depth inside the crust is defined by the thermal gradient.
>
> "At the steady state, as the outside surface sublimates and slowly recedes, there is a feedback mechanism keeping these levels at the same depth: the feedback is controlled by the thermal insulation of ices and the heat flow through the nucleus.
>
> "The upper layers cannot retain any appreciable fraction of CH_4 or NH_3, because the partial pressure of gaseous CH_4 or NH_3 escaping through the snow needles is lower than the dissociation pressures of the hydrates for the temperature of the needles. The temperature itself is controlled by the thermal gradient through the crust."

A problem common to all theories is the source of the tremendous amounts of gas given off by a comet at each perihelion passage. It cannot be assumed that some of the particles are frozen gases since they would be destroyed during the first perihelion passage. Levin's work on adsorbed gases seemed to offer possibilities (Ref. 12). The process was feasible and the energetics were right. However, the mass of gas available comes nowhere near meeting that required for even one orbit, and it is impossible to replace it from the interplanetary medium for the next orbit even if it were sufficient for the first (Ref. 14). A somewhat related problem faced by any comet model is survival from a close perihelion passage. A family of Sun-grazing comets of at least seven members is known, the most recent of which was 1965f Ikeya-Seki. These comets pass within about one solar radius of the solar surface at perihelion. Becklin and Westphal, assuming the emissivities of iron, were able to fit observations of the head of Ikeya-Seki at 1.65, 2.2, 3.4, and 10 μ with a color temperature curve that reached 1000°K at 0.15 AU (Ref. 37). At perihelion the temperature must have been several times that value, far above the vaporization temperature of iron. Indeed any particle of up to several meters radius should certainly be vaporized during a passage within four radii of the Sun (Ref. 15). Whipple has shown that only about 2 percent of the original comet would be available for recondensation, the remainder having been dissipated owing to its gaseous random thermal velocities, together with light pressure effects as particles begin to recondense (Ref. 30). Yet Ikeya-Seki appeared virtually the same before and after perihelion passage.

As has been noted in the section on orbits, secular accelerations have been reported for a number of comets. If these accelerations are real, the icy conglomerate model offers an explanation and the sandbank model does not. As also noted, the effect may not be real. The sandbank model offers no explanation of cometary outbursts other than collision with a fairly large body. Such outbursts appear to happen rather often for such an explanation. However, at large solar distances the icy conglomerate model also has its problems in explaining outbursts, and collisions have often been discussed as the possible cause (Ref. 30).

There remain areas that are complete puzzles, such as the mechanism whereby molecules are ionized in a comet. The solar ultraviolet is not intense enough to account for the measured ionization rate (Ref. 17). If the ionization is due to corpuscular radiation (or ultraviolet) from the Sun, why do the tail particles not stream back from the entire head rather than only from a region very close to the nucleus (Ref. 17)? Phillips has pointed out that the identity of the "parent" molecules is by no means certain (Ref. 38). He quotes work by Stief and De Carlo which indicates that N_2H_4 may be a more likely source of NH than NH_3, and similarly that C_2H_2 may be the best source of C_2 (best in the sense of best fitting the observed spectra of comets). The existence of the forbidden lines of atomic oxygen presents another problem.

Although problems in detail certainly exist, there seems to be no insuperable problem demanding immediate discard of the icy conglomerate model. This is far different from saying it is a "true" description of a comet. That description will only come much further along in the space program.

E. Origin and Evolution

Knowledge of the origin of comets is in roughly the same state as knowledge of the origin of the solar system: there are many ideas, none of them very good, or at least none of them very well developed. Knowledge of the evolution of comets is slightly better because they evolve very rapidly, and there is observational evidence of change.

Orbital evolution has been discussed in the section on orbital characteristics. Secular changes in brightness are also known. Whipple and Douglas-Hamilton have shown that the absolute brightness of P/Encke has decreased secularly by more than four magnitudes in the last 150 years and that the comet may die completely between 1990 and 2000 as a visible gas-producing object (Ref. 39). There is considerable uncertainty in the date of its disappearance because sporadic changes in the luminosity during any given passage are large compared to the secular changes and because it is difficult to be sure old visual measurements of brightness are on the same scale as modern photographic determinations. Whipple and Douglas-Hamilton give the period from 1978 to 1985 as likely for the disappearance of P/Faye (Ref. 39). Even the famous P/Halley has shown a decrease in brightness of about 2½ magnitudes in the past 1200 years, as nearly as can be determined (Ref. 9). This is simply further proof that comets are very short-lived, once they become short-period objects.

Comets that are still in their prime are sometimes seen to split into two or more. Comet 1882 II, one of the famous Sun-grazers, split into five pieces after perihelion passage. It is thought that all seven known Sun-grazers and perhaps others not yet known may be fragments of a single parent comet (Ref. 9). P/Biela was seen to split into two distinct comets in 1846. Both pieces returned in 1852 separated by almost 3×10^6 km. Neither has since been seen. Comet Ikeya-Seki split shortly after its perihelion passage in 1965. Although the differential velocity of the separate nuclei was not great enough to cause two distinct comets to appear, the separating nuclei were well photographed.

Stefanik has listed 13 split comets, of which three were apparently split by tidal forces (1882 II, Ikeya-Seki, and 1889 V P/Brooks 2) (Ref. 40). Radioactive differentiation, followed by thermal shock, has been proposed as one explanation of nontidal splitting (Ref. 33). Whatever the cause of splitting, the result is rapid evolution toward extinction for the comet.

Some 100 years ago, Kirkwood first suspected that meteor streams were the disintegration products of comets. This has proved to be the case. Stream meteors follow the usual cometary orbits, some of the well known swarms being associated with known comets still in existence, e.g., the Perseid swarm and P/Swift-Tuttle, or the Taurids and P/Encke. It is generally stated that no known recovered meteorite has ever resulted from a meteor shower. Nevertheless, Öpik feels that most of our recovered stones and irons are also cometary (rather than asteroidal) debris (Ref. 41).

Every indication, all those just mentioned plus the "quantitative" measures of mass and mass loss per apparition previously discussed, is that an *average* comet can survive no more than perhaps 100 passages nearer than 1 or 2 AU from the Sun without giving up its store of the gas and dust that make it a visible comet. It has already been stated that periodic comets result from planetary perturbations, mostly by Jupiter, acting on long-period comets, but where does the great reservoir of long-period comets originate and how big is it? What is the origin of comets?

Theories of cometary origin can be divided into two major classes, those based on interstellar origin and those based on origin within the gravitational bounds of the solar system. The idea of interstellar origin dates back to Laplace. In the classic form of this theory, comets were condensations in interstellar space. The original velocity distribution of the comets and the presence or lack of a resisting medium at the time of capture vary from theory to theory. There is no question that under some of the conditions postulated, comets could be captured by the Sun. The chief problem is accounting for the fact that strongly hyperbolic comets, which should be the rule on such an origin, do not appear to exist. Only special classes of distribution functions of cometary velocities result in an ellipse rather than a hyperbola as the preferred "capture" orbit.

Some theories regard the capture process as being over, a temporary event as the Sun passed through an interstellar cloud. Others assume that comets are a natural part of interstellar space, filling the size spectrum between interstellar dust and small planets. A very recent theory of this type is that of Sekanina (Ref. 3).

Perhaps the most ingenous theory of interstellar origin is that of Lyttleton (Ref. 15). He observes that the Sun travels through an interstellar dust cloud from time to time. The individual dust particles must then describe hyperbolic trajectories with respect to the Sun that intersect along a line parallel to the relative velocity vector of the cloud and the Sun. The particles are, in effect, gravitationally focused. Kinetic energy is lost through inelastic collisions, and material within about 100 to 1000 AU may be captured by the Sun, depending upon the relative speed of the cloud. This accretion process certainly should work whenever the Sun passes through an appropriate dust cloud; however, the sandbank that would result seems to have insufficient resemblance to what is called a comet.

Theories of origin within the solar system are also quite old, dating back to Lagrange. Most of the 19th century theories assumed comets were ejected by the major planets. The modern champion of the ejection hypothesis is Vsekhsviatsky, who in his more recent papers has partially turned from the major planets to their satellities as the source (Ref. 42). The major objection to the ejection hypothesis has come in modern time with a better understanding of the conditions on the major planets and their satellites. Very few scientists are willing to accept the idea that a mass of 10^{19} g (a large comet) could be ejected volcanically from bodies such as we think the major planets and their satellites to be.

The most prominent current theory is that of Oort, based in part on work of van Woerkom. It states that there is a great reservoir of comets, the total number being perhaps 10^{11}, at a mean distance from 30,000 to 100,000 AU (Ref. 43). These are said to be perturbed into the central part of the solar system by passing stars. As evidence of this reservoir, a plot of the number of comets against the reciprocal semimajor axis is drawn and shows a great preponderance at very large distances. Actually the statistics are so poor, with most of the "reservoir" lying completely beyond the data points, that the "evidence" is very weak. The evidence in no way denies the existence of the reservoir, but neither does it confirm it. Oort's hypothesis in no way creates comets. It only moves the history one step further back.

The origin of the Oort cloud of comets has been discussed by various authors. A very recent study by Öpik indicates that comets could not have been formed at very large distances from the Sun but rather must have been formed in the region of the major planets in the early history of the solar system and perturbed out into the reservoir (Ref. 44). The assumption is that in those early times there was a sufficient density of material about, remnants of the solar nebula, to create comets. If the average comet has a mass of 10^{17} g, the mass of 10^{11} of them is only about two Earth masses, a rather sizable amount of matter but still a small fraction of the combined mass of Jupiter and Saturn. It is a bit disconcerting to suggest the comets were formed within the planetary system, thrown out, perturbed back in, then perturbed to periodic comets in some cases, left alone in some, and thrown completely back out of the system again in others. Comets become a sort of cosmic yo-yo.

Richter notes an interesting comment by Hoffmeister (Ref. 45). If other planetary systems are abundant and have comets that they throw away on hyperbolic orbits from time to time, there may be a number of comets in interstellar space, and we may observe one from time to time on a strongly hyperbolic trajectory, even though the origin is within a planetary system.

Knowledge of the origin of comets is in a highly speculative state. Once we are sure what a comet really is, after the first comet probe, perhaps some firmer theory can be constructed.

IV. Scientific Objectives and Experiments

A. General

The Space Science Board of the National Academy of Sciences (Ref. 46) has developed a rationale for exploration of the solar system. They stated that the exploration of the solar system is concerned with three central scientific problems of our time. These problems are defined as:

(1) The origin and evolution of the Earth, Sun, and planets (moons, asteroids, and comets implied),

(2) The origin and evolution of life, and

(3) The dynamical processes that shape man's terrestrial environment.

In terms of these major problems, they have further suggested a number of specific questions to guide cometary research. Some of these are shown in Table 1.

Obviously, the mission under consideration in this document cannot logically be addressed to the task of answering all of the questions specified by the Space Science Board, so some ordering is required. It would seem that the important questions can be divided into two groups. The first group is concerned with questions regarding the physical nature and composition of the comet itself. For example, are cometary nuclei made up of single bodies of icy material, and if so, what compounds do the ices comprise? What is the chemical nature of the material? Is the so-called sandbank model appropriate, and if so, what are the nature and distribution of particles? The second group is concerned with questions regarding the interaction of the cometary matter with solar corpuscular and electromagnetic radiation, and with interplanetary magnetic fields. For example, how are tail gases ionized? How are they accelerated away from the Sun? If by the solar wind, what is the

Table 1. Some scientific questions

Question	Solution
1. Are cometary nuclei single bodies of icy material?	A TV or bistatic radar experiment in a near flyby seems best. See experiments 1 and 2 in Table 2.
2. If so, what compounds do the ices comprise?	An infrared, ultraviolet, or microwave experiment could give direct evidence about the composition of the snowball itself. A mass spectrometer could recognize "boil off" products. See experiment 3 in Table 2.
3. What part do frozen free radicals play?	See 2 above.
4. What is the structure of cometary dust?	A detailed answer will require a sophisticated approach involving sample return or complex on-board analysis of samples. Some information can be obtained by observing abrasion and penetration rate of spacecraft components during passage through the comet.
5. Do stable isotope ratios in icy compounds or dust differ from the usual terrestrial and meteoritic values?	An answer will require a sophisticated approach involving sample return or complex on-board analysis of samples. Perhaps a good infrared experiment could answer this.
6. What is the age of the dust?	See 5 above.
7. Can nuclear material be identified as primordial solar system condensates or as accumulated interstellar dust grains?	Unknown. The answer to this question can only come from an evolution of knowledge about comets and the solar system.
8. How long, on the average, have the present elliptical comets been in orbit?	Information about the boil-off rate, or how rapidly comets are affected and the mechanism of this, may suggest a solution. See experiment 3.
9. What is the composition and size distribution of cometary dust?	Information on the composition will probably require sample return or on-board analysis techniques. A penetration or *Pegasus*-type experiment would be useful for determining the size distribution. A simple dust detector (see 4 above) will give much information on the mass velocity and energy distribution.
10. How are tail gases ionized?	The search coil magnetometer, vector magnetometer, energetic electron detectors in the range of a few to tens of kev, plasma detector, mass spectrometer, ultraviolet spectrometer, and perhaps TV experiments can each contribute to an understanding of this phenomenon.
11. How are they accelerated away from the Sun; if by the solar wind, what is the coupling mechanism?	See 10 above.
12. What causes cometary bursts?	See 10 above.
13. What are the compositions of coma and tail gases?	Infrared and ultraviolet spectroscopic studies using both ground and spacecraft techniques will be useful. A mass spectrometer on a fly-through trajectory can provide some direct measurements. See experiment 3.

coupling mechanism? What is the effect of cosmic ray bombardment?

From the foregoing, it seems appropriate that the scientific objectives for this preliminary mission study should be to investigate the comet at close proximity with experiments designed to determine its physical state, structure, and composition, and how it reacts to its environment. A select scientific payload to accomplish these broad objectives could comprise the following experiments: (1) Photo-imaging, (2) Mass spectrometer, (3) Dust (solid particle) detector, (4) Magnetic field detector, (5) Plasma spectrometer, (6) Fourier spectrometer, and (7) Cometary mass determination.

In the following paragraphs, the experiments above are discussed in more detail. Table 2 presents a résumé of the text material.

B. Scientific Experiments

1. Photo-imaging experiment. The primary objective of the photo-imaging experiment is to obtain closeup views of the comet nucleus. Other objectives are to photograph the coma prior to and during encounter.

Specific objectives for the imaging system are:

1. Obtain information about the macroscopic construction of the comet nucleus. Resolutions on the order of 0.05 km/picture element are necessary.
2. Obtain nucleus albedo measurements.
3. Obtain information about the density of the nucleus.
4. Obtain imaging-science-related measurements on the coma (polarimetry and color if applicable).
5. Obtain a continuous-approach view as the spacecraft nears the comet.
6. Provide a continuous flow of video information throughout encounter with the comet so as to study radio noise and attenuation-propagation effects.

The trajectory characteristics ($\approx$10 km/sec relative speed to the comet nucleus and 2500-km closest approach) along with communication and data recording limitations ($\approx$1–2 k bits/sec and 10^7 bits respectively) force some very special design problems on this system. In addition, the cometary coma from large distances is very dim ($\approx 10^{-4}$ ft lamberts), whereas the comet nucleus can be as bright as 4×10^3 ft lamberts, depending upon the comet's proximity to the Sun. In order to satisfy the broad assumptions previously outlined, a system with the following general characteristics is suggested.

A two-camera system with field-of-view ratios not to exceed 10 to 1 and with both cameras boresighted with a comet-nucleus-seeker is envisioned. Both cameras should have imaging tubes characterized by variable electronic shuttering capabilities ($\approx$100 to 1) and with sensitivities presently exhibited by SEC vidicons. In addition, the wide-angle camera should have a variable iris of approximately five to seven *f*/stops in order to encompass the full exposure range necessary for pre-encounter and encounter

Table 2. Scientific experiments

Experiment	Weight, lb	Power, w	Objective
1. Photo-imaging	50	32 (maximum)	To examine the nucleus, if present, and determine its shape, size, albedo and light-scattering properties, and also to examine the overall structure of the comet and observe any temporal and spatial changes.
2. Mass spectrometer	12	15 (maximum)	To investigate the chemical nature of the gaseous material making up the coma, and to determine the distribution of such species and ionized constituents as can be identified.
3. Solid particles	10	2	To investigate the distribution, mass, and velocity of small solid particles throughout the coma and in space.
4. Magnetic fields (a 3-axis helium magnetometer plus a single-axis search coil magnetometer)	8	7	To examine magnetic fields in space and in the comet, and to investigate interaction between the comet and the ambient solar environment.
5. Plasma spectrometer	20	10	To examine plasma streams in the comet and in space and to obtain data on the interaction that must occur between the solar plasma and the cometary atmosphere.
6. Fourier spectrometer	26	12	To examine at close range the gaseous envelope around the nucleus to decide on the origin of the radicals C_2, CN, etc.
7. Cometary mass	N/A	N/A	To determine the mass of the cometary nucleus as it may be indicated by tracking data.

operations. The wide-angle camera should have averaged video and peak video automatic exposure control devices selectable by ground command, whereas the narrow-angle camera should have only peak video automatic exposure control.

Two operational modes, necessitating a tape recorder for each camera chain (although with different storage capability), are anticipated. The first or pre-encounter mode would be one in which several (3 to 5) wide-angle pictures are obtained, recorded, and played back immediately at the rate of about 3 frames/hour. Each picture would have a raster of 500 × 500 at a 6-bit encoding level. On-board data compression could reduce this encoding bit level. Upon completion of the readout, the sequence would be repeated either automatically or by ground command. This pre-encounter mode could begin as long as 40 hours before encounter and could include both color and polarimetry experiments, in addition to verifying the comet-seeker operation.

The second or encounter mode could be clock- or ground-commanded, and would feature the narrow-angle photography of the nucleus. Approximately 6–7 pictures of 500 × 500 × 6-bit encoding could be recorded, with the picture sequencing spaced over a few minutes or a few hours. Tape readout could be commanded immediately or delayed until emergence from the coma in preference to Mode 1 operations. The narrow-angle camera tape playback could be repeated several times if desired.

Table 3. Typical camera characteristics for comet-intercept experiment

Characteristic	Type or value	
	Camera A	Camera B
Parameters		
Field of view, deg	0.5	5 (or less)
Focal length, cm	100	10
Iris	f/8 to f/22 (fixed aperture)	f/1 or f/2 variable to f/22
Shutter (electronic), sec	10^{-3} variable to 10^{-5}	5 variable to 0.005
Raster, lines	500 × 500	500 × 500
Lens type	Cassegrain	Conventional
Weight, lb		
Lens	8–15	3–11 (depending on minimum f/no)
Electronics	< 15	< 15
Total	23–30 (15–22 on scan platform)	18–26 (10–18 on scan platform)
Volume, in.[a]	14 × 6 × 6, plus 12 × 6 × 4 on platform (lens)	17 × 6 × 4 on platform
Tube type	SEC vidicon or 2-in. orthicon	
Power consumption, w	32 (average)	
Auxiliary equipment required	(a) 2 digital data recorders, 1 with ≈ 10^7-bit storage, 1 with 5 × 10^6-bit storage (b) Mechanical platform with 2 degrees of freedom (c) Comet sensor boresighted with camera	
Data rate, bps	1–2 × 10^3	

[a] 14 × 5 × 4 total off platform.

The system parameters shown in Table 3 represent a typical set of camera characteristics that would satisfy the experiment requirements, based upon current state-of-the-art assumptions.

2. *Mass spectrometer.* Through the utilization of Earth-based spectroscopic observations, a number of neutral and ionized gaseous species have been observed in the emission spectra of comets. The positively identified gases in order of increasing molecular weight are shown in Table 4.

Table 4. Gases identified in emission spectra of comets

Gas	Molecular weight
CH	13
CH^+	13
CH_2	14
NH	15
NH_2	16
OH	17
OH^+	17
Na	23
C_2	24
CN	26
CO^+	28
N_2	28
C_3	36
CO_2	44

It is believed that the observed molecular gases are due to the photodissociation (and ionization) of more complex parent molecules such as CH_4, NH_3, H_2O, N_2, CO_2, and C_2N_2, which have not as yet been identified in the spectra of comets, since their spectra occur in inaccessible wavelength regions. Meteoritic material contains H_2, CH_4, CO, N_2, H_2S, CO_2, and SO_2. It is conceivable that a great many of the observed molecules could be derived from a meteoritic gas source. However, sulfur-bearing compounds have never been observed in cometary spectra. If comets are made up of meteoritic material, it is possible that the proposed comet-intercept missions might detect sulfur-bearing molecules if suitable instrumentation, such as a mass spectrometer, were included in the scientific payload.

In addition to the observed neutral and ionized gases, there should be appreciable amounts of He, Ne, and Ar associated with any comet. These inert gases can be identified in mass spectra with little difficulty and their isotopic ratios readily determined The isotopic ratios of the inert gases vary greatly in nature, depending on the source of the gas. For example, in the Earth's atmosphere, neon-20 is by far the most abundant isotope, and even neon-22 is far more abundant than neon-21. In neon that has been produced by nuclear spallation due to cosmic-ray bombardment, as in some meteorites, all three isotopes of neon are nearly equally abundant. Helium-4 can accumulate through long-lived radioactive decay; the abundance of argon-40 is similarly augmented. Because isotopic variations can arise in various ways in the inert gases, their measurement can provide significant clues to the nature and origin of comets.

Spectra indicating a gaseous atmosphere in the makeup of a comet occur only near the perihelion of the orbit, i.e., when the comet is close enough to the Sun to receive sufficient solar radiation to excite an observable emission spectrum. In addition, two theories prevail that require the comet to be close to the Sun in order to obtain a gaseous atmosphere—observable or not. The first, attributable to Lyttleton, proposes that in the vicinity of the Sun the probability for collisions between cometary particulate material increases drastically. The violence of these collisions causes local heating at parts of the surface of the solid particles, so that gas occluded in the solid material is "boiled" off to form an atmosphere. The second, more generally accepted theory (attributable to Levin), proposes that gases are absorbed on or in the cometary solid material and that, on close approach to the Sun, the heating of the solid material by solar radiation is sufficient to offset the heat of absorption of the absorbed gas molecules, giving rise to a gaseous atmosphere.

A mass spectrometer placed on a comet-intercept mission could be constructed to sample the gaseous atmosphere in the molecular density range of tens of molecules per cm^3 to 10^7 molecules per cm^3. It would detect both ionized and neutral species merely by inhibiting the instrument's ionizing mechanism required to convert neutral molecules to ions for the purpose of detection.

Since a mass spectrometer in flight configuration would only be able to resolve unit masses in the mass range of $M = 1$ to $M = 100$, substantial overlapping of different molecules at the same nominal mass number could lead to confusing mass spectra (e.g., CO and N_2 at $M = 28$, NH_2 and CH_4 at $M = 16$, NH and CH_3 at $M = 15$, etc). This problem arises since normally unstable molecules resulting from photodissociation are likely to be quite abundant in a cometary atmosphere; their mean free paths will be very long and the probability for recombination of these molecules upon collision with other molecules or surfaces will be extremely minute. A highly calibrated mass spectrometer operating with variable ionizing electron energies will be required to circumvent the major portion of this problem. In addition, spectra will have to be taken in both the ionizing and nonionizing modes.

The instrument presently conceived as applicable to cometary gas analysis is a quadrupole mass spectrometer. The instrument is anticipated to weigh on the order of 12 lb and consume 15 w of power (maximum). It records data in a digital mode by mass-analyzing (1) ions created in its ion source through electron impact on neutral species, and (2) primary ions trapped in an accelerating field with the ionizing electron source inhibited. The mass-analyzer portion of the instrument is entirely nonmagnetic, being composed of superimposed ac and dc voltages impressed on a set of four parallel rods. Mass-scanning of the spectrometer is accomplished by slaving the analyzer voltages to the address register of a multichannel scaler (MCS). Ion pulses arriving at an electron multiplier detector are amplified and stored in the appropriate MCS channels according to their mass. The data in the MCS are then telemetered.

Since there likely will be a high relative velocity between the mass spectrometer and the cometary gases ($\approx$10–30 km/sec) provision must be made to trap primary ions of this energy as well as to focus the neutral particles of the same energy that are ionized in the mass spectrometer. High voltages will be used in the ionizing and trapping region for this purpose. In doing this, however, a positive bias voltage must likewise be used on the quadrupole rod assembly so that ions remain in the analyzing field long enough to be sorted according to their mass.

In addition, it is highly desirable to mount the mass spectrometer on a scan platform so that absolute molecular density data can be obtained. It will be necessary to take mass spectral data both in the direction of the spacecraft velocity vector and against it.

3. ***Solid-particle detector.*** The purpose of this experiment is to measure the relative-velocity vector, the mass, and the distribution of small solid particles in a comet. This type of information would be extremely interesting from several points of view:

(1) The structure and nature of a comet.

(2) The distribution of particles, masses, and velocities for cometary dust, and its relationship to that found for interplanetary dust. This bears on the question of a cometary origin of interplanetary dust particles.

(3) The dynamics of dust tails. This could provide a positive check on the classical (radiation pressure) theory for the formation of these tails.

The overall extent of a cometary dust cloud might far exceed the observed size of a coma, which can be as large as 10^{11} cm, and accordingly the counts of dust particles should begin as far out from the coma intercept as possible. A tube of 1 cm^2 cross-section across the comet could be expected to contain a total mass on the order of 5×10^{-3} g for a comet of 10^{18}-g mass and radius of 10^{10} cm; therefore, a detector of 1000 cm^2 cross-section placed transverse to the direction of passage through the comet would be expected to encounter a few grams of material. If the material is finely divided, say of masses less than 10^{-3} g, and distributed throughout the coma, then many thousands of impacts may be recorded.

The basic detector is similar to that proposed by W. M. Alexander et al. for the *OGO* series of terrestrial satellites. It is formed from a combination of an acoustic sensor and elements for collecting charge from minute plasma clouds. First the particle penetrates a thin metallic film (500 to 1000 angstroms thick) and produces a small plasma cloud. The dust particle proceeds down the tubular portion of the detector and impacts on the acoustical sensor. A second plasma cloud is formed at this final destructive impact. The impacting dust particle delivers to the acoustical sensor a mechanical impulse that is closely related to the momentum of the impacting particle. The charged plasma clouds provide the signals from which a time-of-flight measurement is made. The measured momentum and speed determine the mass of each dust particle. The charge collected from the second plasma cloud is related to the kinetic energy of the dust particle. By using the measured speed and kinetic energy, an independent determination of the particle mass can be made. Three such tubular detectors should be used to form the experiment package.

The instrument should have a sensitivity of approximately 10^7 dyne-sec and a weight of 10 lb, should use 1 w of power and have a data rate of 15 bits per sample, with a sampling interval every 2 min during coma passage. The three detector horns should be directed orthogonally, with one looking toward the Sun, one away from the Sun, and the third back in the direction from which the comet is intercepting the spacecraft.

4. ***Magnetic field detector.*** The two-fold significance of magnetic field measurements lies in what can be learned about the gas tail of the comet and about the nature of any interaction between the coma and the magnetized solar wind. No empirical knowledge exists concerning intrinsic magnetic fields, but what is known about the nucleus and the coma makes it seem improbable that either could give rise to a significant field. If this is true, the only fields of interest must originate as solar-interplanetary fields that are modified by interacting with the comet.

Because it consists basically of neutral gases, the coma is unlike the media that have customarily been involved in studies of the interaction of the solar wind with obstacles such as the Earth's magnetosphere or the solid body of the Moon. The nature of the interaction cannot be predicted with certainty, and therefore important implications for plasma physics may result. However, the most likely consequence of direct measurement would be to permit a choice between reasonable alternatives. Since the observation of significantly different conditions near the comet would be important, the kinds of measurements that are now being made near Earth should be contemplated. In addition to plasma measurements and magnetic field measurements, the observation of energetic electrons and relatively high-frequency electric and magnetic field variations would be beneficial.

Magnetic fields are widely thought to play a significant role in all aspects of the cometary tail, including its formation, structure, and dynamics. The ions that constitute the tail are supposedly formed in the interaction region between the coma and the solar wind. One proposed ionization mechanism is charge exchange between the neutral atoms in the coma and the solar wind protons. It has also been suggested that a more important mechanism is ionization by collision, with energetic electrons generated in the bow shock expected to form as the hypersonic solar plasma is deflected around the comet. It is well known that the typical structure of gas tails, as well as their orientation relative to the Sun and to the cometary velocity vector, is undoubtedly the effect of solar-wind pressure. However, the lateral dimensions and especially the length of the tail are likely to be associated with the properties of the magnetic field in the tail. Regarding tail dynamics, motions have been observed, including corkscrew-like features, that are presumed to be due to large-scale magnetic fields.

A magnetometer carried on a cometary probe should be able to map the gross features of the magnetic fields in various parts of the comet and study the extent and nature of their disordering. The feature that would be expected to occur farthest from the comet is a detached bow shock. The nature of the fields in the magnetosheath between the shock front and the coma proper could be established. It would also be important to investigate the occurrence of an inner boundary to the magnetosheath that would partition the coma into an ionized and unionized region. If such a boundary exists, it would be important to study its characteristics. The basic magnetic properties of the tail are obviously also of considerable interest, such as its interface with the shocked solar plasma and the possible development of a neutral sheet where the intensity of the magnetic field in the tail approaches zero.

Instrumentation currently being used to make interplanetary magnetic field measurements would be entirely appropriate for a comet mission. Either a flux gate or a helium magnetometer could accomplish the scientific objectives. Inclusion of a search coil magnetometer-spectrum analyzer would be desirable, both to help unequivocally identify features such as the bow shock and to ascertain the intensity and character of waves with frequency components up to ≈ 1000 hours. Typical weight and power requirements for a standard three-axis magnetometer are 5 lb and 3 to 5 w. A single-axis search coil magnetometer and analyzer would weight 2 to 3 lb and use less than 2 w. Data rates of 10 to 100 bps should be entirely adequate for either magnetometer. Significant results are possible at lower bit rates but such a reduction seems unnecessary in view of the probable high-rate data requirements of other on-board experiments such as photo-imaging.

*5. **Plasma spectrometer.*** A plasma spectrometer in the vicinity of a comet could probably obtain data leading to the solution of two important problems in the physics of comets: namely, what is the source of ionization of the cometary matter, and what is the nature of the mechanism that couples the ions to the solar wind to give the observed direction and the observed time variations of a Type I comet tail. Proposed ionization mechanisms are (1) charge exchange with solar-wind protons, (2) photoionization by solar ultraviolet radiation, (3) ionization by energetic electrons accelerated in a cometary bow shock, or (4) some other mechanism, as yet not understood. A trajectory passing on the sunward side of the cometary nucleus would be the most productive for studying the ionization-mechanism problem; however, a bow shock might be detectable by plasma detectors and magnetometers even on a dark-side trajectory. Information necessary for the generation of a model describing the coupling mechanism could be obtained by determining the mass distribution of positive ions and the vector-velocity distributions of both positive ions and electrons as functions of distance from the axis of the Type I tail.

Instrumentation currently being used to make interplanetary and near-Earth plasma measurements could almost certainly be adequately modified for a comet mission. Modification would be necessary to achieve the extended range of energy-to-charge and flux required for this mission; for example, energy-to-charge values as high as 50 or 100 kv would be necessary to detect any CO_2 ions moving with the speed of the undisturbed solar wind, while the flux of any such energetic molecular ions is probably appreciably lower than the proton and alpha flux levels usually encountered in the solar wind. Neither of these modifications is outside the state of the art. If the spacecraft does not spin, further modifications will also be required owing to the probable deflection of the solar-wind flow around the comet. The electrostatic analyzers with closely spaced curved plates, which might be used to reach the higher energy-to-charge values, generally have very narrow angular apertures. Thus several detectors looking in different directions might be necessary.

The minimum useful plasma experiment would probably weigh about 5 lb and require 2 w of power and a data rate of 10 bps. A better, more complete plasma experiment might weigh 20 lb, draw 10 w, and require 100 to 1000 bps.

6. Fourier spectrometer. On approaching the Sun, many comets exhibit emission lines, in addition to a pure-reflection spectrum, that show the presence of free gases in both neutral and ionized forms consisting mainly of radicals associated with easily volatilized substances such as CH, CN, NH, OH, CH^+, OH^+, and many others. For some comets that pass close to the Sun, lines of sodium, nickel, iron, and possibly chromium have been detected. The atoms, molecules, radicals, and solid particles observed are believed to originate either in a solid nucleus consisting most probably of ices of various compounds, such as H_2O, NH_3, CO_2, etc., which are partly in the form of solid hydrates with an admixture of meteoritic material, or from single discrete particles scattered throughout the comet, but concentrated mainly in the head. The excitation mechanism is most probably fluorescence from solar radiation; however, an ionization energy resulting from particle collisions when the comet literally turns itself inside-out on the perihelion side of the orbit has been suggested.

The present knowledge of the constitution of cometary atmospheres has come mostly from Earth-based spectroscopy. However, these measurements are restricted in spatial resolution and by the Earth's atmosphere. An infrared Fourier spectrometer on a spacecraft that passed through a comet would not be restricted by the Earth's atmosphere, and its spatial and spectral resolution could be such as to provide basic new data on the nature, physical properties distribution, and origin of the cometary atmosphere.

The objective of this experiment is to perform high-resolution infrared spectroscopy in the 1.2- to 5-micron spectral region in order to identify atoms, molecules, and radicals forming the cometary atmosphere and to determine their spatial and time distribution in relation to any observed nucleus and throughout the coma and tail. Slit spectrograms of the gaseous envelope closest to the nucleus should be taken during the close-flyby portion of the mission to determine the origin of the radicals and molecules observed near the nucleus—that is, whether they are contained in the nucleus itself or broken off stable molecules at some distance from the nucleus.

The instrument should have a spectral resolution of 0.5 cm^{-1}. It would weigh about 26 lb and use 12 w of power. Because it would share a scan platform with the photo-imaging experiment, it could be pointed at select regions of the comet during the approach, intercept, and recession phases of the mission. The data requirements would be about 3×10^5 bits per interferogram, and several of these would be desired for each phase of the mission. It should be noted that for this experiment, or a similar ultraviolet or infrared emissivity sensor, the number of possible measurements will depend upon the brightness of the comet and the resulting integration time required to get sufficient signal to noise for an interferogram.

7. Cometary mass determination. No comet has a known mass; however, the periodic comets Lexell and Brooks 2 have passed directly through the satellite system of Jupiter without creating any detectable perturbation in the satellites. This would seem to indicate that comets are either very diffuse or of low mass.

Photometric observations of many comets, in conjunction with assumptions on the albedo and assumptions that the observed reflected sunlight originates in a spherical body, have led to estimates for the diameter of the nucleus ranging from 0.1 to 10 km. If a specific gravity is assumed for this hypothetical body, then a mass can be computed. It appears that the masses of comets probably lie in the range of 10^{15} to 10^{21} g. This is quite small; however, if a mass of, say, 10^{18} g filled a more or less solid sphere of a few kilometers, then an acceleration approaching in value the solar acceleration of 0.6 cm sec^{-2} at 1 AU might exist near the surface of the nucleus.

V. Conclusion

Considering the many questions about cometary phenomena that still remain unanswered, and the possible importance of these questions in cosmogonical research, it is concluded that a comet–intercept space probe mission is potentially the most important mission for the purposes of such research, within the capabilities of the early 1970's.

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