A REVIEW OF THE PHYSICS OF COMETS AND ITS EXPERIMENTAL INVESTIGATION BY AN INSTRUMENTED SPACE PROBE

Prepared by

W. Bernstein
R. Doolittle

SPACE TECHNOLOGY LABORATORIES, INC.
Redondo Beach, California

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Prepared:
W. Bernstein
Physical Electronics Laboratory

Prepared: R. Doolittle
R. Doolittle
Space Physics Department

Approved: C.D. Graves
C. D. Graves
Associate Manager
Space Physics Department

Approved:
R. B. Muchmore
Director
Physical Research Division

SPACE PHYSICS DEPARTMENT

PHYSICAL RESEARCH DIVISION

SPACE TECHNOLOGY LABORATORIES, INC.
One Space Park
Redondo Beach, California

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1. General Physical Processes in Comets

A comet has been defined as a composite body, surrounded by a gaseous atmosphere, and moving around the sun in an elongated orbit, crossing the plane of the ecliptic at any angle. (Of particular interest in the study of comets have been general astronomical observations (occurrence and orbits), the structure and composition, the physical and chemical properties and their behavior in the particular environment of the comet, and the inferences from these observations as to the creation, life and general cosmological significance of comets. This report will first try to summarize some of the available knowledge of comets and their behavior and also point out areas where significant questions still exist, and will then attempt to evaluate the information to be derived from a cometary flight.) It should be pointed out at the onset that comets are individual apparitions, and that many of the statements applied to the general group are thus only qualitative in nature. It should also be pointed out that studies of comets are difficult and that, until recently, visual observation rather than photometric determinations of brightness and spectral emission, have provided the bulk of data with respect to comets.

Comets, in general, are postulated to consist of a rather small nucleus, composed of solid material, a gaseous envelope called the coma, and a less dense gaseous region called the tail. The nucleus is believed to be only several kilometers in diameter, the coma perhaps 10^4 - 10^5 kilometers in diameter and the tail region about 10^6 kilometers long and 10^4 kilometers wide.

The presently accepted model of the nucleus is the "icy conglomerate" model proposed by Whipple in which the nucleus consists of a mass of frozen gases containing interspersed solid micrometeorite particles. This model offers significant advantages over the previously accepted "sand bank" model in which the nucleus was postulated to consist of small solid particles; the gas supply was occluded and absorbed gases. The "icy conglomerate" model suggests a much larger gas reservoir and in addition can explain the survival of comets at small heliocentric distances where the solar thermal energy input and the tidal force is large. An upper limit to the cometary mass is set by the fact that comets do not appear to exert any observable gravitational effects on close passage to planets or their satellites; lower limits to the cometary mass are set by cometary survival at small heliocentric distances although the disruptive effects depend largely upon the assumed physical structure. In general, the cometary mass is assumed to be 10^{17} - 10^{20} gms.

Evidence for the presence of solid material is derived from two sources. Firstly, meteor streams are known to be associated with comets. Secondly, some of the light observed from the coma and certain tails has the spectrum and polarization characteristic of reflected sunlight. Observation of the emission spectra of some meteors on entry into the earth's atmosphere are characteristic of iron.

Thus the present idea is that the frozen gaseous surface is sublimed by the solar thermal radiation as the comet approaches the sun. Interspersed with the gases are micrometeorite fragments. In the newer comets, where "new" is meant to imply that the comet has not completed many solar orbits, the rate of solid particle emission is enhanced with respect to the gases. This presumably implies that in the older comets, the solid material occurs in larger fragments; it is not clear how this agglomeration occurs in the presumably frozen nucleus.

As the comet approaches the sun, the sublimation of material from the surface of the nucleus increases. The brightness of the comet increases rapidly, which is accounted for by the increase of solar radiation intensity and the increase in density of the radiating gases and reflecting particles. The emission from the coma consists of the molecular spectra of a wide variety of neutral free radicals including CN, C_2, C_3, NH, NH_2, Na, and the ionized stable molecules CO^+, N_2^+ and CO_2^+. The dimensions of the coma appear to be different depending upon the spectral region observed which indicates a variable distribution of molecular species. The densities in the coma are believed to range from 10^{10}/cc near the nucleus to perhaps 10^3 at the periphery. Although the surface temperature of the icy nucleus is probably $10^\circ - 100^\circ$K, it is reasonable that the sublimed molecules have a temperature of $100^\circ - 500^\circ$K. If the density is sufficiently low so that collisions do not occur, then the expansion velocity is about 1 kilometer/sec. The density, estimated from the emission intensity, and the expansion velocity give the rate of gas loss from the nucleus; the "icy conglomerate" model was proposed to account for these loss rates.

It is probable that the gaseous molecular emission is the result of photo-excitation by solar radiation rather than collisional processes because of the low densities. Although only the spectra of free radicals are observed, it has been assumed that the parent molecules are the simplest stable molecules which can be dissociated to yield the observed free radicals. In the "icy conglomerate" model, it is therefore assumed that these stable molecules consistute the solid material. It is also true that solar radiation will dissociate these molecules which may then recombine to other stable molecules ($2 H_2O \longrightarrow H_2O_2 + H_2$). Explosive chemical reactions between these new molecules are possible and the sudden increases in cometary brightness are attributed to these sources. It is reasonable to propose, however, that the recombination of these free radicals can lead to rather complex molecules with, as yet, unknown chemical properties.

The mechanism for ionization of the molecules is unclear. It is unfortunate that those molecules which radiate well in the ionized state radiate only weakly in the neutral state and vice versa. Thus the simultaneous observation of the density of ionized and neutral states of a particular molecule, as a function of distance from the nucleus, is not possible. However, there is evidence that no single ionization process is sufficient to account for the observed behavior of the different molecular constituents. The radiated intensity pattern in the coma for CN indicates that the neutral lifetime is in the order of 10^5 sec, whereas the appearance of CO^+ reasonably close to the nucleus indicates a lifetime of only 10^3 sec for CO. The ionization potentials for both molecules are about 14 ev; the difference in the geometrical appearance of the ionization infers at least an active ionization mechanism in addition to charge-exchange or photo-ionization processes, perhaps chemical in nature. The observed cometary molecular spectra are similar to those observed in low temperature laboratory gases of similar composition; however the relative intensities of the same bands are different. This can be explained if it is assumed that the cometary radiation is the result of solar photo-excitation and the observed intensities are thus modified by the known intensity variations in the solar spectrum.

Two types of comet tails have been observed; although usually only one type is present in any comet, both may occur simultaneously or the tail may be completely absent. One type consists mainly of solid particles and shows a pronounced curvature which indicates the absence of any large solar repulsive force. The light from these tails is reflected sunlight; these tails are characteristic of "new" comets. The other tail type consists of ionized stable molecules identified by their characteristic emission spectrum. These tails show only little curvature indicating a solar repulsive force greater than the attractive solar gravitational force. The ions identified include CO^+, N_2^+, and CO_2^+; the abundance of other ions has not been established. The observation of streamers and filaments with a relatively long lifetime, similar to those observed in a variety of gas discharges in magnetic fields, implies that magnetic fields are associated with cometary phenomena.

It was first believed that the observed steady state accleration of the tail could be attributed to the solar radiation pressure. However, calculations by Wurm indicated that the radiation - CO^+ cross-section (CO^+ is the most abundant observed ion) is too small for radiation pressure to account for the observed accelerations. The correlation, sometimes rather poor, between solar activity and enhanced comet brightness and more violent tail accelerations led Biermann to propose that corpuscular emission from the sun (solar wind) was the source of the observed acceleration. Biermann suggested that charge exchange between the solar plasma and the neutral gas in the coma was the dominant ionization mechanism, and that the tail acceleration resulted from momentum transfers between electrons in the solar plasma and the cometary ions. If reasonable values of the comet tail density were used (10^3/cc), densities in the order of 10^5/cc were required in the solar wind to yield the observed acceleration. Both direct and inferential estimates of the solar wind density indicated an upper limit of about 10^3/cc for the steady state density; thus Biermann's collisional interaction was too small. However, several possible collective plasma interactions are known which would essentially greatly increase the probability for momentum transfer; these may be of either the electrostatic or hydromagnetic type and are discussed in detail by Hoyle and Harwit.[40, 41] The collisionless electrostatic shock which occurs as a result of unstable plasma oscillation arising from the interaction of two plasma clouds had been postulated by Kahn and Parker and Noerdlinger as a possible source for the observed superthermal particles in the earth's radiation belts. Recent calculation by Noerdlinger[42] and Ek, et al[43] indicate that a high ratio of directed to thermal velocity for both electrons and ions is required for the instability to occur and that the instability proceeds first as an electron-electron interaction followed by the ion-ion interaction. Hoyle and Harwit suggest that the electron-electron instability is possible only in the initial transient interaction between the solar wind and cometary plasma; the result of the instability would be a heating of the cometary electrons so that, in steady state, the instability would not occur. This analysis is probably valid as long as no energy loss process for the cometary electrons can occur so that the electron temperature remains high. Probably collisional loss processes (inelastic collisions) are absent at the low densitites. However, radiation might be expected at the plasma frequency ($\sim$1 mc); Scarf[44] had advanced some arguments for the radiation only of the higher harmonics of f_p. The observation of low frequency electromagnetic radiation associated with comets is questionable.

Thus in the absence of electron energy loss processes, Hoyle and Harwit conclude that electrostatic instabilities cannot account for the observed tail accelerations and that the interaction must be hydromagnetic. This interaction requires the existence of a cometary magnetic field which Hoyle and Harwit postulate arises in the following manner. It is rather likely that the solar wind retains some trapped magnetic field (circulating currents) since it is presumed to be hydromagnetic in origin. As a result of charge exchange between the relatively stationary cometary neutrals and the solar protons, the solar wind magnetic field is decelerated and trapped in the comet plasma. The interaction of further solar plasma on this trapped field exerts a pressure on the cometary plasma which, with perhaps reasonable assumptions of mass and density, can account for the observed acceleration.

There are several theories for the role of comets in the cosmology of the solar system. It has generally been believed that comets cannot enter the solar system from the galaxy because of the relative absence of hyperbolic orbits; the few observed hyperbolic orbits probably arise as a result of perturbations by Jupiter. Possible sources of comets may be the following: Condensation of portions of the solar nebulae at the time of planet formation, association with the formation of the asteroids, or trapping of material by the sun during passage through a particularly dense and active interstellar cloud. It is quite clear that the lifetime of comets in a small heliocentric orbit is small (10^5 years) because of the high rate of material loss and solar disruptive effects. It is also reasonably clear that recondensation or accretion of new material cannot greatly increase cometary life. It is reasonable to assume therefore that a rather large number of comets exist in very large orbits beyond Pluto, where they are not subject to solar effects. These comets are randomly perturbed into observable orbits by the combined effects of the outer planets and perhaps stellar perturbations. The comets represent the principle source for the meteor streams and also perhaps for the interplanetary dust. As a consequence of the Poynting - Robertson effect, the interplanetary dust is swept into the sun, and its replenishment is necessary to maintain the observed steady state conditions.

There is perhaps only one significant piece of information which might suggest an extra-solar system origin for cometary material. The C^{12}, C^{13} ratio, as determined by the isotope shift observed in the CN molecular bands, is variable from comet to comet, and ranges from the high values characteristic of the solar system to the low values characteristic of the carbon rich stars. The implication of these observations is rather unclear at present.

Although the comet-meteor stream relationship has been well established, the relationship of comets and meteorites is less well understood. Since meteorites are, in general, absent in very old deposits in the earth's crust, the general conclusion has been that meteorites are of recent origin as the result of the disintegration of a planet. A relationship between meteorites and comets thus also infers a recent origin for the comets. It is possible that, as a result of a planet's disintegration, material may have been distributed into distant orbits; however, the solid material would probably be rather large in size and this conflicts to a degree with Whipple's icy conglomerate comet model and does not explain the origin of the required gas reservoirs.

2. Cometary Experiments

It is pertinent to ask what information might be desirable in order to obtain a more complete understanding of the physical and chemical nature of comets and their interaction with their environment, and whether a suitably instrumented flight in the near vicinity of a comet could yield important information. In the following sections a number of possible experiments are discussed which could be included into a space probe payload at the present time, i.e., with existing instruments and technology. The final sections contain a discussion of significant measurements that might be included as future comet probe experiments. It must be pointed out that, in general, a single experiment or measurement, while contributing to the general scientific knowledge of comets, will not in itself necessarily resolve any of the basic outstanding questions of cometary phenomena. These basic categories are concerned with 1) structure, 2) plasma interactions, and 3) chemical composition. Some currently possible experiments appropriate to each are discussed below.

2.1 Present Payload Experiments

2.1.1 Structure

2.1.1.1 Television

Undoubtedly, photography of the nucleus from short distances would be valuable in confirming the icy conglomerate model, and in confirming present ideas of the nuclear size and mass. If we assume that the encounter between the probe and the comet occurs at 1 AU from the sun and that the nucleus of the comet is visible by reflected sunlight with a 10-percent reflectivity, then the total energy flux per unit area reflected by the nucleus is 1.4×10^5 ergs/cm^2/sec over all wavelengths. If we further assume a miss distance of 10^4 km and treat the nucleus as a sphere of radius R cm, then the energy flux entering an objective lens of diameter D cm. will be given by

$$\frac{1.4 \times 10^5 \cdot 4\pi R^2}{4\pi \times (10^9)^2} \cdot \frac{\pi D^2}{4} = 1.1\, R^2 D^2 \times 10^{-13} \text{ ergs/sec}$$

If the lens transmits 50 percent of the energy falling on it then the energy flux per resolution element incident on the photocathode of the television camera tube will be $5.5\, R^2 D^2 \times 10^{-14}$ ergs/sec. Of the total reflected solar energy incident on the TV tube cathode, only a fraction is effective due to the spectral response of the photocathode. If we choose the interval from 3000 Å to 6500 Å this represents about 43 percent of the solar energy flux. Thus the effective flux on the TV tube is

$2.36\ R^2D^2 \times 10^{-14}$ ergs/sec.

Let us choose a telescope such as the Questar, whose physical dimensions are easily incorporated into a space probe payload. This instrument has a focal length of 120 cm. and an aperture of F/11. The diameter of the image then will be $2.4\ R \times 10^{-7}$ cm. Let us now assume a nuclear radius of 1 km = 10^5 cm. Then the image diameter equals 2.4×10^{-2} cm and the image area equals $\frac{\pi(2.4)^2 \times 10^{-4}}{4} = 4.52 \times 10^{-4}$ cm^2. The television system will probably require some kind of storage prior to telemetry read out. Therefore, a storage videcon pick-up tube is suggested. The best resolution that can be achieved is about 1000 lines/in. at 10^{-2} ft-candles illumination and with 1/30 second integration time. This means a minimum energy density of 2.93×10^{-2} erg/cm^2 is needed. From the above image area a minimum total energy of $(4.52 \times 10^{-4})\ (2.93 \times 10^{-2}) = 1.325 \times 10^{-5}$ ergs must fall on the photocathode. This in turn will require an exposure time of $2.36\ R^2D^2 \times 10^{-14}$ seconds. The effective diameter of the lens is given by $D = \frac{f}{F}$ where f is the focal length and F is the f-number. Then $D = \frac{120}{11} = 10.9$ cm. For $R = 10^5$ cm, the minimum exposure time is 4.72×10^{-4} seconds.

Now 1000 lines/inch resolution means resolution elements of about 6.45×10^{-6} cm^2. Therefore, the image will cover $\frac{4.52 \times 10^{-4}}{6.45 \times 10^{-6}} = 70$ resolution elements. The area of the nucleus treated as a circular disk is $\pi R^2 = 3.14 \times 10^{10}$ cm^2 so that we resolve elements of surface area equal to $\frac{3.14 \times 10^{10}}{70} = 4.5 \times 10^8$ cm^2. This corresponds to linear elements on the comet of 2.1×10^4 cm or 0.21 km. The only way this can be improved is to use a longer focal length lens or achieve a miss distance less than 10^4 km.

The above calculations have been based on an attitude controlled, non-spinning vehicle such that the videcon tube can view the comet for at least 4.72×10^{-4} seconds with negligible lateral displacement of the image. Suppose now that the vehicle is spinning at 2 revolutions/sec and that the look direction is at right angles to the spin axis. In 4.72×10^{-4} seconds, then, the camera will sweep out $4\pi \times 4.72 \times 10^{-4} = 5.93 \times 10^{-3}$ radians. At 10^4 km, there are 10^{-4} radians/km so in the time requied for the exposure we sweep out $5.93 \times 10 = 59.3$ km, which of course completely smears out the image.

In general, distance swept out in km = $.493\ \omega$ where ω is revolutions/min. The resultant resolution, in km, due to the lateral motion superimposed on the intrinsic resolution of the system is given by $\sqrt{(.21)^2 + (.493\omega)^2}$. If we accept a final resolution of .3 km, then $\omega = .43$ revolutions/minute. If it is not desirable to de-spin this much or less, then of course much detail of the nuclear surface is lost.

The telemetry problem does not appear too difficult since only about 70 resolution elements are involved with, say, 5 levels of grey. This would be 350 bits of information per picture. This information could be placed in a buffer storage and additional pictures could then probably be taken. It may also be of interest to obtain pictures in different wavelength regions by using filters. If we take, say, four pictures at 15 minute intervals, then the telemetry rate would be only about 1/3 per second. Let us then assign 1 bit/sec for the television.

Due to the fact that at 10^4 km the image of the nucleus only occupies a small fraction of the available television field, a sensing error of

$\pm 10^{-2}$ radians from the probe-nucleus vector would still allow the image of the nucleus to fall on the television tube cathode. Some kind of optical sensing device will be necessary to locate the optical center of gravity of the comet which is presumably the location of the nucleus. After a sufficient time for tracking and scanning by the sensor, the television camera would be turned on and the picture recorded.

A ruggedized television camera with a slow scan videcon tube, such as has been developed by Hallamore Electronics, would represent a typical system. Such a unit would weigh 7 pounds and consume about 9 watts of power.

2.1.1.2 Micrometeorite Experiment

Measurements of the abundance and mass of the solid particles in the coma would contribute to a knowledge of the nuclear structure and also possibly to the knowledge of meteor streams. Since the polarization and intensity of the continum portion of the cometary spectra, as observed by terrestrial telescopes, depends on the nature, size distribution, and shape of the scattering particles, any information pertaining to these parameters would greatly enhance the interpretation of the spectrum.

Many types of micrometeorite and dust particle detectors have been developed and flown in the past so that the "state of the art" is well developed. If we choose a comet such as 1957c (Encke), then the dust density as estimated from the intensity of the continum is $10^{-9}/\text{cm}^3$. at $4 - 9 \times 10^4$ km. Assuming a relative velocity of 15 km/sec between the probe and the comet, then with a detector of area 350 cm^2 we could expect about one impact every two seconds. A minimum momentum impact sensitivity of 10^{-5} dyne-sec would detect particles of mass about 7×10^{-12} grams at the above velocity. If these are spherical iron particles, this results in a minimum radius of about 0.6 micron. A micrometeorite detector such as the one being flown by Alexander on OGO has this order of sensitivity and is capable of measuring any charge which may reside on the particles as well as both the momentum and the energy of the particles. The velocity is determined by a time of flight measurement which is accurate to about 1.5 percent. The information to be read out would be velocity, momentum, charge, and total number of impacts. These could probably all be contained in one 9-bit digital word resulting in a telemetry rate of about 5 bits/second. This type of experiment would weigh less than 10 pounds and consume less than 1 watt of power.

2.1.2 Plasma Interactions

It is doubtful whether measurements of this type in the tail can, in themselves, lead to a complete understanding of the observed accelerations. It is believed that more detailed measurements of the tail properties can, however, distinguish between the electrostatic and hydromagnetic plasma interaction possibilities and also provide a more rigorous test of the various present theories. The significant parameters would be ion density, electron temperature, and the vector magnetic field.

2.1.2.1 Plasma Probe

By measuring the electron temperature, by means of, for instance, a planar ion and electron trap, a great deal could be learned about the interaction between the solar wind and the cometary plasma. In particular, this experiment should be able to resolve the question as to whether the acceleration of ions into the tail is due to electrostatic instabilities in the plasma or whether the interaction is hydromagnetic in origin. In addition, measurements of the solar wind while enroute to the comet would be invaluable.

An ion and electron trap such as the one being developed by Whipple for OGO is capable of measuring the density and temperature of thermal electrons as well as densities, masses, and temperature of thermal ions. Such an instrument is capable of detecting positive or negative currents as small as 10^{-13} amps. This corresponds to 6.25×10^5 electrons/sec. With a relative velocity of 15 km/sec between the probe and the comet and assuming a 20 cm^2 detector area, the minimum detectable electron density would be 2×10^{-2} electrons/cm^3 and similarly for the positive singly charged ions. The information to be read out would be a digital voltage word for each of four electrodes and a digital current word for the electrometer for a total of 45 bits at each sampling. If we sample once per second, then the rate must be 45 bits/sec. The weight of the entire experiment would be about 5-8 pounds and would require about 2 watts of power.

2.1.2.2 Magnetic Fields

Many magnetometers have been flown on satellites and space probes in the past and the state of the art is well advanced to the point where no problems should be expected with placing a magnetometer aboard a comet probe. One would want to measure the vector magnetic field both in interplanetary space and as the probe approached, passed through, and receded from the comet. The magnetometer should have a sensitivity on the order of one gamma or less since this is the order of magnitude of cometary magnetic fields that have been postulated in order to explain certain molecular ionization phenomena and plasma interactions.

A triaxial flux gate magnetometer along with a rubidium vapor magnetometer, so as to obtain independently both the components and the absolute magnitude of the magnetic field, would eliminate the principal disadvantages of either instrument alone. If we assume a range from 0.1 to 3.2 gamma in 0.1 gamma steps, then we need 6 digital bits for each of the flux gate components plus an additional 6 bits for the rubidium vapor information. Thus a total of 24 bits per sampling is required. If we sample twice per second, then the rate is 48 bits/sec. The weight of such a package including electronics would be about 13 pounds and the total power consumption about 8 watts.

2.1.2.3 Contamination Experiment

A third possibility which should be included under plasma interactions would be to contaminate the comet with a suitable substance released from the probe in the vicinity of the comet. If, as is believed, there exists a cometary magnetic field of the order of a few gamma, then the ions produced by photoionization of the contaminant material could become trapped by the field. The observation from the earth of the solar radiation resonantly scattered by these ions could provide some useful information on the nature of the forces involved and the interactions between the ions and the solar wind. As pointed out by Mühch, the lifetime of the phenomena, or the time available for observation, is a function of the mass of contaminant and explicitly $t = \frac{M}{4.55}$ where M is in kilograms and t is in days. Thus a mass of contaminant on the order of 23 kilograms or 51 pounds would result in the ability to observe the motion over a period of 5 days. This is, of course, much longer than an instrumented probe would remain in the vicinity of a comet. Therefore, the contamination experiment is a possible way to study the large scale dynamics of cometary ions.

2.1.3 Chemical Composition

Because of the extended size of the coma and tail, the emitted light intensity would not be increased significantly on close approach so that no appreciable increase in spectral sensitivity could be achieved. It is also presumed that, in the near future, it will be possible to perform spectroscope observations above the earth's atmosphere, thus enabling access to the UV region. Thus it appears that the only spectroscopic gain in a near approach would be an increase in the geometrical resolution and it is questionable as to whether this is necessary. A more rewarding series of experiments directed toward the identification of cometary compounds and the ionization dissociation processes is possible in the coma. Presumably the parent molecules are abundant only in the near vicinity of the nucleus. In general, the spectroscopy of polyatomic molecules is complicated and the laboratory spectra for these molecules are not well known. Thus it would appear that spectroscopic identification of the parents is insufficient and that mass analysis represents the most feasible approach. Some conclusions with respect to dissociation processes can be obtained by observation of the molecular mass distribution as a function of distance from the nucleus. A measurement of the percentage ionization as a function of distance from the nucleus would provide valuable confirmation of the spectroscopic data; even more significant would be the determination of the percentage ionization for the individual molecules which could lead to the proper interpretation of the various ionization mechanisms.

2.1.3.1 Mass Spectrometer

Ion mass spectrometers are currently being developed which will have sensitivities down to 10^{-14} amperes. This corresponds to a flux of singly charged ions of 6.25×10^{4} ions/sec. For a window area of 12 cm^2 and a relative velocity of 15 km/sec, the minimum measurable density will be about 3.5×10^{-3} ions/cm^3. Unfortunately, it is very difficult at the present time to perform a mass analysis of the neutral molecules since the efficiency for ionization by an electron beam is on the order of only 1 in 40,000. However, the relative abundances of the ionized molecules could be measured by this method and this in itself would be a significant experiment. An r.f. ion spectrometer such as the one being developed by Taylor for OGO is capable of measuring positive ion masses from one to forty-five amu. This range includes all the molecular ions that have been observed spectroscopically. From 1 to 6 amu the resolution is 0.5 amu and from 7 to 45 amu the average resolution will be 1 amu. The information sought here will be in the form of an ion current converted to a proportional voltage by the electrometer tubes. Different masses are analyzed and allowed to impinge on a collector electrode by appropriately varying certain grid voltages. Since it is not known definitely a priori just what ion species to expect, the remaining available telemetry should be assigned to this experiment. If the total telemetry capability is 250 bits/sec, then the mass spectrometer would use 151 bits/sec. The total instrument including two spectrometer tubes weighs about 8 pounds, occupies about 1 cubic foot, and consumes about 8 watts of power.

2.1.4 Summary of Payload Experiments

The following table summarizes the weights and power of the presently feasible experiments which could be included as a comet probe payload.

Experiment	Weight (lbs)	Power (Watts)	Telemetry Rate (bits/sec)
TV	7	9	1
Micro-meteorite	10	1	5
Plasma Probe	8	2	45
Magnetometer	13	6	48
Mass Spectrometer	8	8	151
Total	46 (lbs)	28 (watts)	250 (bits/sec)

Thus, with the exception of the contamination experiment which would increase the weight by about 50 pounds, the five experiments above would have a combined weight of 46 pounds and a total power consumption of about 28 watts.

2.2 Future Experiments

It is clear that experiments which can be performed with present "state of the art" techniques yield no information whatsoever with respect to the cosmological significance of comets and only limited information with respect to the radiation chemistry and molecular configuration of cometary material. This section will discuss some of the problems involved and will outline some possible experimental approaches for consideration in future experiments. The ideal future experiment would consist of a landing on the nucleus, sampling of nuclear material, and return of the sample to earth for analysis. If we confine this experiment to the far distant future, there are however other experiments which may be considered.

2.2.1 Elemental Analysis

The elemental constitution of the solid fragments would be most important in establishing the origin of cometary material. The collection and analysis of the micrometeorite fragments could be a reasonable approach to this problem. It is clear, of course, that because of the small sample size fractionation effects during formation would be of major importance and probably only elements with very similar physical properties might coexist in the sample. A reasonable method of analysis might be through neutron activation and subsequent analysis of the activation spectrum. This experiment implies that the isotopic abundances of the studied elements would require an irradiation time of about 1 hour to yield detectable activities. This appears marginally feasible at best with conventional neutron sources, but should be considered as possible.

2.2.2 Isotopic Analysis

Isotopic abundances which could yield information with respect to the time of fragment formation is clearly more difficult. This is further complicated because of cosmic ray bombardment of the small samples so that the isotopic abundances no longer reflect the time of formation. However, if possible, this would be an interesting experiment.

2.2.3 Radiation and Radio Chemistry

The radioactivity expected to be associated with the small solid samples arises from cosmic ray bombardment. The cosmological interpretation of these radiations is doubtful, but rather interesting radio chemical information may be obtained.

2.2.4 Neutral Particle Mass Spectrum

The important radiation chemistry problems would involve a study of the parent molecules sublimed from the nucleus and a direct determination of the ratio of ionized to unionized abundance of a given molecule. It is believed that ion mass spectroscopy is feasible in the coma and tail. However, the mass spectroscopy of neutral molecules is more difficult because of the low efficiency of ionization. The development of neutral particle mass spectrometers for particle densities less than 10^6/cc remains to be done.

2.3 Some Scientific Constraints on Mission Requirements

In this section we shall examine some specific comets in greater detail with particular regard to which comets seem most suitable to investigate with the proposed experiments and how the scientific results are affected as a function of miss distance.

It must be understood, at the outset, that numbers pertaining to cometary dimensions, ion and dust densities, and other physical properties of comets that have been deduced from terrestrial observations, are at best only order of magnitude values. These numbers will vary considerably, of course, depending on which specific assumptions one imposes on the comet and which interpretation one gives to the experimental observations.

As was already pointed out, a comet, in general, can be divided into three physical regions: the nucleus, the coma, and the tail. The nucleus probably consists of frozen gases interspersed with solid micrometeorite particles ("icy conglomerate" model) and has a diameter on the order of several kilometers. As the comet approaches the sun, the material at the surface of the nucleus sublimes as a result of the effect of the solar radiation. The density of sublimed gases and particles increases as the heliocentric distance decreases. These materials form the coma and are responsible for the observed molecular emission spectra; the brightness increasing as the comet approaches perihelion. The dimensions of the coma are different as viewed in different regions of the spectrum indicated a non-uniform distribution of molecular species. In general, the coma extends from 10^4 - 10^5 kilometers in diameter. The molecules in the coma are neutral free radicals that have been dissociated from stable parent molecules as well as ionized species.

The third region, the tail, consists primarily of ionized stable molecules and small solid particles. The dimensions of the tail are perhaps 10^6 kilometers long and 10^4 kilometers wide. Not all of the proposed experiments could be best accomplished in only one of these regions. We shall first specify the particular region of interest for each experiment.

The television picture, of course, is concerned with the solid nucleus. The micrometeorite experiment would deal principally with the coma. The plasma probe and magnetometer would be most useful in the tail but important information could also be obtained in the coma. Finally, the ion mass spectrometer would probably be most useful in the coma since something might then be said about the neutral molecules from a measurement of the ion densities in this region. This, of course, does not rule out the possibility that significant results might be obtained in the tail.

Let us now look at a few specific "typical" comets for which molecular ion and dust density estimates have been made. From photoelectric and spectroscopic observations of Encke (1957c) and Giacobini-Zinner (1959b), the density of CO^+ molecules near the head ($\sim 10^4$ km) is of the order of 1 to 100 molecules/cm^3. The average dust densities for these comets are of the order of 10^{-19} to 10^{-24} gm/cm^3. For comet Arend-Roland (1956b) the dust densities are of the order of 10^{-11} to 10^{-14} gm/cm^3. It can be seen that not only are these densities very small but the estimates range over many orders of magnitude. For a micrometeorite detector with a minimum sensitivity of 10^{-5} dyne-sec, and a relative velocity of 15 km/sec between the probe and the comet, one could detect spherical iron particles of minimum radius 0.6 microns or spherical CO_2 particles of minimum radius 1.0 micron. From the intensity of the continuum and certain assumptions regarding the number and density of the solid particles, the radius of the particles is believed to be of the order of 0.5 microns. If the area of the detector is 350 cm^2 then the number of impacts per second = $5 \times 10^8 \rho$ where ρ is the dust density in particles/cm^3. For comparison, the dust density of Encke is believed to be $\sim 10^{-9}$ particles/cm^3 and for a "dusty" comet, such as Giacobini-Zinner, it is $\sim 10^{-7}$ particles/cm^3. Thus the impact rates seem reasonable as long as the momentum is sufficient.

As with molecular and dust densities the dimensions of cometary nuclei are subject to considerable uncertainties. Most estimates of nuclear radii are based on observations of visual magnitudes. To convert this information to a nuclear radius requires a knowledge of the albedo, A. We do not know the value of A for cometary nuclei. The lowest value ever observed, on astronomical objects is 0.028 (for Ceres) and the highest one is 0.61 (for Venus). These maximum and minimum values result in the following radii:

Encke (1957c) 0.67 - 4 km
Halley-Peltier (1936a) 25-60 km
Giacobini-Zinner (1959b) 0.72-4.6 km
Mrkos (1957d) 3.93-232 km
Bester (1948I) 7-41 km
Winnecke (1927) 0.17-0.80 km
Bappu (1949c) 8.3 - 36 km

For a miss distance of 10^4 km we could obtain a resolution of 0.2 km at the surface of the nucleus with the system described in section 2.1.1.1. This should be sufficient to resolve some structure for most nuclei. There can be no doubt, in general, that in order to make any significant measurements with the presently proposed experiments, the probe must penetrate the coma to at least 10 percent of the distance to the nucleus. This means a miss distance of less than 10^4 km. In addition, in order to learn something of the dynamics involved in the tail from the plasma probe and magnetometer, the probe must also pass through the tail. As far as the experiments themselves are concerned there is no particular reason to prefer one comet to another except perhaps one whose motion is retrograde, such as Halley's or Temple-Tuttle which would thereby increase the probe-comet relative velocity as well as enabling the probe to traverse the tail longitudinally.

It would seem that the most important phase of the comet probe study is that of guidance. In order for the experiments to be successful the probe must definitely encounter the comet. This means that the orbit of the comet must be known or determined with great accuracy. This, in turn, probably implies choosing a periodic comet whose past apparitions have been most recently and frequently observed and hence one whose approach could be predicted in advance and which could be tracked for perhaps 8-10 months before perihelion. Two such short period comets are Encke and Pons-Winnecke. On the other hand, unexpected comets are sometimes discovered and accurate orbit parameters determined many months before closest geocentric approach. Such a comet would also be a desirable target.

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