POSSIBLE CONTRIBUTIONS OF SPACE EXPERIMENTS TO COMETARY PHYSICS[1]

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Comets are astrophysically interesting objects from various points of view. The interpretation of their geometric, spectroscopic and photometric behavior involves such considerations as low-temperature physics, fluorescence, photochemistry, sublimation, magnetohydrodynamics, charge transfer and scattering. Many observed phenomena have not yet received convincing explanations. Yet the comets may eventually furnish essential data on the formation and evolution of the solar system, as well as on the interplanetary space and solar activity.

Physical characteristics of comets

What are the known essential physical characteristics of comets? The atoms, molecules and solid particles of the coma and tail originate in a nucleus consisting most probably of ices of such various compounds as H_2O, NH_3 and CO_2, partly in the form of solid hydrates, with an admixture of "meteoritic" material (metals, silicates, etc.). The observed gases in the head and tail are atoms, and di- or triatomic radicals or molecules (atoms and neutral radicals in the coma: Na, O, Fe, CN, CH, OH, NH, C_2, C_3, NH_2; ionized molecules in the tail: CO^+, N_2^+, CO_2^+). They result from the photo-dissociation or the ionization of stable parent molecules (H_2O, NH_3, CO_2, . . .), or from chemical reactions occurring near the surface of the nucleus; some radicals may also have been imbedded in the frozen matrix. The gases, except atomic oxygen, emit their characteristic electronic spectra as fluorescence excited by the electromagnetic radiation of the sun. They have a limited life, and eventually dissociate or become ionized; they fade out into interplanetary space. The D-lines of atomic sodium are only emitted at small heliocentric distances; the forbidden transitions of oxygen are observed at the same heliocentric distances as the radicals of the coma; certain iron lines have been observed in one comet at an extremely small heliocentric distance. The gaseous densities in the head and tail are so low that no thermodynamic equilibrium prevails: the intensity distributions within the observed bands lead to vibrational and rotational "temperatures," which have widely differing values for different molecules (from 50° K to 4000° K), and which are thus purely artificial. The absolute and relative molecular abundances differ in different comets.

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Occasionally, the tail spectrum may be much stronger than the head emission (Comets Morehouse 1908 III and Humason 1961e). It should be noted that the tail emission bands are due to the ions of stable molecules (CO, CO_2, N_2); only ionization by solar corpuscular radiation is needed, not photodissociation by solar electromagnetic radiation.

In addition to the discrete emissions, most cometary heads and many tails reveal a solar continuum. Actually, when comets are at very large heliocentric distances, the diffuse head gives only a solar spectrum, while at small heliocentric distances, the head shows a discrete emission spectrum superimposed on a solar spectrum. In practically all the spectroscopic investigations of comets the emphasis has been placed on the discrete emissions. The study of the continuum has usually been neglected, although it may eventually provide important information on cometary and interplanetary physics and on cosmology. Recent discussions (Swings, 1962a) have shown that the continuum of the cometary heads is due to scattering by solid particles, but we are still ignorant of the nature, shapes, and size distributions of these solid particles.

Cometary tails, as well as heads, occasionally reveal a continuum that is certainly also due to scattering of the solar radiation by small solid particles. There is no compelling reason for assuming that the particles of the tail are of the same nature, shapes or sizes as those present in the head: the tail particles are repelled to large distances from the nucleus, while the head particles exhibit an approximately spherical distribution.

Determination of the abundances in cometary heads and tails is difficult, even for the molecules that give rise to the observed emissions. Of course these abundances decrease with increasing distance from the nucleus, and they differ from one comet to another. For C_2 and CN the order of magnitude is 10^4 to 10^6 per cm^3 near the nucleus of a "gaseous" comet, 10^2 to 10^3 molecules per cm^3 at 10,000 km from the nucleus. Similar values are found for CO^+ in the brightest parts of tails. On the other hand, we know nothing on the abundances of the di- or polyatomic molecules or radicals whose resonance spectra do not fall in the observable region, such as the stable molecules H_2 (which may be abundant), N_2, CO, NO, NH_3, H_2O, . . ., the radicals CH_2, CH_3, . . . or the ion NH^+.

Our ideas on the amount of dust in heads or tails are also extremely vague. The explanation of the observed scattered continua of "dust comets" requires less than one icy particle of diameter smaller than 1 μ per cubic meter of the head.

Despite numerous important recent papers on comets, we do not know with certainty the nature and the release mechanism of the parent molecules, the exact mechanisms of dissociation and ionization, or the abundances of the molecules other than those whose resonance transitions happen to be in the observable region. Our ideas are still very vague on the formation and behavior of the tails. While the icy conglomerate model of the nucleus appears satisfactory, we wish to know much more about the nuclei and about the outbursts. How does the solar wind react with the cometary atmosphere? Do magnetic fields play a role? Are there genetic families of comets? What are the nature, sizes and shapes of the solid particles? Many essential questions indeed remain unanswered.

Obtaining cometary data

Obviously, we have not yet fully exploited the possibilities of observations from the surface of the earth. We have very little information on the infrared and radio spectra, even in the spectral ranges accessible from the ground. Infrared work from high-altitude balloons or aircraft is desirable; a Michelson interferometer with Fourier transformation would be particularly helpful for such work. The predicted infrared cometary emissions have been published recently (Swings, 1962b).[3] Accurate photometric and polarization measurements in well-defined spectral regions (including the scattered solar continuum) are badly needed; they should be made at specific locations in the head and tail. High-resolution photographs, taken in fairly rapid succession and covering given spectral regions, will still reveal important information on the tails. We need a variety of spectrograms, especially with high resolution. We know too little of C_3, NH_2, OH^+ and [OI] in the head; we know practically nothing of the whole visual and near-infrared regions of the tail.

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[3] Essentially, the near-infrared region is characterized by vibration-rotation transitions of molecules. We may hope to find the fundamental (1-0) transitions of the radicals observed in the usual region; of other diatomic molecules, such as CO; of certain probable parent molecules, such as NH_3, CO_2, H_2O, etc.; and of intermediate radicals, such as CH_2 or CH_3. However, we do not know what excitation mechanisms prevail. If the vibration-rotation bands are excited by fluorescence only, they will be extremely weak, since the integrated solar energy for $\lambda > 2.5\ \mu$ represents only 2 percent of the total solar energy, and since the transition probabilities of the vibration-rotation bands are low compared to the usual electronic transitions. However, other mechanisms may play a major role for these emissions of low energy. For example, after the emission of the (0,1) band of the $^2\Sigma$ - $^2\Sigma$ electronic system of CN, the CN radicals will be left on the v" = 1 level of the ground electronic state, from which they will emit the fundamental (1-0) vibration band if they are not de-excited by another electronic absorption. Moreover, the vibration bands may also be excited by other mechanisms that release small amounts of energy.
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No tail spectrum has ever been obtained with a resolution that permits a discussion of the excitation mechanism. We even need better objective prism-pictures, especially in the [OI] wavelengths. In the spectral region λ7000 to λ9000 of cometary heads, only the (2.0) and (3.1) emissions of the red system of CN have been observed with certainty. We know little about the color, spectrum and polarization of distant comets. Our observational knowledge of the dimensions, colors, temperature and magnetic properties of the nuclei is still practically nonexistent. Accurate photometric observations should be made of the dimming of stars observed "behind" a comet at small angular distances from the nuclei; the observations by Dossin (1962) are only of the pioneering type. Actually, observations of the occultation of radio stars by cometary heads and tails would give us valuable information on the electron densities in cometary atmospheres: one should be on the lookout for the possibility of such occultations whenever a sufficiently precise cometary ephemeris is available.

Actually, much laboratory work also remains highly desirable to seek descriptions and analyses of such various band systems as C_3; discovery of such new systems as C_2^+; experimental and theoretical determinations of f-values for all observed molecular systems; determination of cross sections for dissociation or ionization of the observed and probable parent molecules. In preparation for future observations in the far ultraviolet, a great deal of additional laboratory spectroscopic work in the Schumann region is required. Progress in infrared instrumentation is also needed.

(footnote 3 continued)

Part of these infrared observations could be made from balloons or aircraft. The main remaining trouble in the case of observations from a balloon or a high-flying aircraft results from the ozone absorptions near 4.8, 9.6 and 14 μ. The main absorption by CO_2, which takes place near 4.3 and 15 μ (less important near 1.5, 1.6, 2.0, 2.6 and 3.3 μ), would be greatly reduced. The effect of H_2O--which is the main obstacle at ground level: bands near 0.9, 1.1, 1.4, 1.9, 2.5 to 2.9, 5.0 to 7.5 μ, and beyond 20 μ--would be considerably reduced.

At ground level the ν_3 parallel band of CO_2 near 4.26 μ, if emitted by a comet, would be re-absorbed in our atmosphere. Similarly, cometary bands of H_2O (ν_2 from 5.35 to 7 μ) and probably of NH_3 (ν_4, P branch from 6.15 to 6.88 μ and R branch from 5.62 to 6.02 μ) would be absorbed by telluric water vapor. Atmospheric CO_2 would absorb the following bands of comets: CO_2 (P branch from 15.015 to 15.698 μ; R branch from 14.268 to 14.927 μ), probably HCN (P branch from 14.154 to 15.373 μ) and probably C_2H_2 (from 13.887 to 14.601 μ). The ozone band near 4.8 μ would absorb part of the CN and CN^+ cometary emissions. It would be interesting to try to observe from the ground whatever infrared cometary emission escapes from telluric absorption

Such endeavors from the ground --or better from a high-altitude balloon or aircraft-- should of course precede any attempt from a satellite.

Yet, as in various other chapters of astrophysics, a major breakthrough in the field of cometary physics requires space observations. It is probable that only a comet probe will reveal the true natures of the nucleus of the solid particles and parent molecules of the head and tail, and of the main physical mechanisms involved, including the magnetic and magnetohydrodynamic effects. Information on the far-ultraviolet spectrum should also be gathered. Moreover, artificial gaseous and solid comets should be launched and observed with telescopic, photometric, spectrographic and polarizing devices. The various ways to obtain cometary data will be examined in succession.

a) Far-ultraviolet observations - It may be hoped that some "colorimetric" far-ultraviolet information will be obtained from the survey programs that will be carried in future orbiting astronomical observatories, especially the Celescope. Eventually, we hope to secure spectrometric data with a spectral resolution similar to that in the usual region (in wave-number units per mm); such detailed information will have to wait until powerful orbiting telescopes and slit spectrometers become available.

What should we expect? Of course, the unexpected will be more exciting. Nevertheless, it may be interesting to venture a few predictions. Since the amount of solar radiation short of $\lambda 3000$ represents only one percent of the total amount of solar electromagnetic energy, we may expect that the ultraviolet cometary spectrum will be very weak, compared with the usual spectral range.

It appears impossible to foresee the intensity and spectral distribution of the scattered ultraviolet solar spectrum. As for the ultraviolet cometary emissions themselves, it is reasonable to assume that they are excited by the same fluorescence mechanism as the cometary bands of the ordinary region. The ultraviolet region offers a possibility to discover such cometary molecules and atoms as H_2, N_2, O_2, NH^+, CN^+, N, O and C, whose resonance transitions are short of $\lambda 3000$ A.

Important differences arise in the excited emissions. In the region $3000 > \lambda > 1700$ A, the exciting solar radiation is mainly the continuum; of course, the profiles of the corresponding excited bands will be distorted by the solar absorption and emission lines. This distortion is more pronounced than in the usual range, because of the greater number of absorption lines, and also because of the presence of discrete emissions, such as the Si II lines. But for λ shorter than 1500 A the exciting solar radiation is mainly in the form of discrete lines, plus the Lyman, He I and He II continua. If cometary emissions are excited by radiations $\lambda < 1500$ A, they will thus not be real bands, but discrete resonance series, at least if secondary effects are not involved. There is a narrow spectral region in which the solar continuum and the discrete solar emissions may play an equal role. It is clear also that excitation by discrete emissions will be very sensitive to the radial velocity of the sun relative to the comet; in particular, the ultraviolet pre- and post-perihelion spectra of a comet may be entirely different.

The possible resonance series of H_2, N_2, N_2^+, CN^+ and NH^+ have been predicted recently (Swings, 1962b).

b) Artificial gaseous comets - These should be high-altitude releases of gases that are expected to be stable parent molecules in comets, such as NH_3, H_2O, CO_2, CO, possibly CH_4 (methane), C_2H_2(acetylene), C_2N_2 (dicyanogen), HCN (hydrogen cyanide), $(NH_2)_2$ (hydrazine), C_3H_4 (methyl acetylene), H_2O_2 (hydrogen peroxide). Their photodissociation in the field of solar radiation should give rise to the cometary radicals CN, C_2, C_3, CH, NH_2, NH, OH. The NH_3 may produce NH_2 and NH; $(CN)_2$ may give rise to CN; C_3H_4 to C_3, C_2 and CH; H_2O and H_2O_2 to OH; $(NH_2)_2$ to NH_2 and NH; etc. The CO_2 and CO are of interest only insofar as they lead to the corresponding ions, but production of CO^+ and CO_2^+ by photoionization would be too slow.

The photolysis by the solar ultraviolet radiation may theoretically be predicted on the basis of elaborate laboratory work. At the present time, however, such predictions cannot be made because the effective cross sections are practically unknown, except (partly) for NH_3, CH_4 and H_2O. Actually, the photolysis may possibly be studied more reliably and with greater accuracy from rocket experiments performed at twilight than from delicate laboratory work, combined with the complex intensity distribution in the solar spectrum.

Since certain liberated radicals would react rapidly with free atomic oxygen, the release should in most cases take place at a fairly high altitude, where the atmospheric free O-atoms are rare, i.e., at 400 to 800 km.

At first sight such experiments do not seem too difficult. In certain cases, as for NH_3 (probably the most interesting example), it may be best to carry the substances in the liquid form. At the time of the explosive release of the liquid, part of the substance will be rapidly evaporated, freezing the remainder. For other compounds more elaborate techniques may be applied in order to produce a sufficient number of radicals.

Interesting information is provided on this problem by the "Saturn High Water Experiment" (Debus, Johnson, Hembree and Lundquist, 1962). Eighty-six tons of water, carried as ballast in the upper stages of the Saturn rocket, were released by explosive rupture of the tanks at an altitude of 105 km. Visually, a rapidly expanding cloud, which reached a diameter of the order of 10 km in from 2 to 3 seconds, was observed.

Of the released 86,000 kgs of water, a portion of about 14,000 kgs (16 percent) was released as vapor in the high atmosphere. The photodissociation of H_2O-vapor by solar ultraviolet radiation, $\lambda < 1850$ A,

$$H_2O + h\nu_{\odot} \rightarrow OH + O$$

is slow, and the reaction of the OH-radicals with the atmospheric oxygen atoms

$$OH + O \rightarrow H + O_2$$

is relatively fast. Hence, only a small fraction of the H_2O vapor was converted into OH-radicals. From calculations by Potter (1962) the number of OH-radicals in the cloud in the early stages of the release seems to be of the order of 10^{25}, but this figure may be off by a considerable factor (it amounts only to 300 grams of OH-radicals, or about 2.10^{-5} of the quantity of vapor). In the daytime observation this number of OH-radicals could probably not have been detected. Let us compare it with the number of OH-radicals in a cometary head, hence compare the OH-surface brightness of the High Water (HW) cloud, with the OH-surface brightness of a typical comet.[4]

Let us consider a HW-cloud, 3 km in diameter, whose angular diameter is 30.10^{-3} radian. Following Potter, let us assume that it contains a total number of OH-radicals of the order of 6×10^{24}. Let us now examine the OH-region of a cometary head situated at 1 a.u. from the sun and the earth; it seems that a mean density of 10^3 OH-radicals per cm^3 is a reasonable figure for an ordinary comet. We assume a diameter of 150,000 km for the OH-head (this overestimation does not affect the result).

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[4] A fairly large quantity of fuel and of liquid oxygen was also released. In the cloud, owing to the fuel, there may have been fluorescent emissions of the CH, C_2, C_3, and CH_2 radicals, which are also of cometary interest. However, the reactions of these radicals with atomic O are also rapid. The photolysis seems too complex to predict the abundance of the resulting radicals.

The number of OH-radicals in the OH-head is (volume x density)

$$n\ (OH) \cong 2.10^{33}\ .$$

The angular diameter of the OH-head is approximately 10^{-3} radian. To obtain the same OH-surface brightness for the HW-cloud as for the comet, we need

$$n_{HW}(OH) \cong 10^{24}\ .$$

Thus, if we adopt the number of OH-radicals estimated by Potter and a mean OH-cometary abundance of $10^3/cm^3$ the OH-surface brightness of the HW-cloud would be a few (about 10) times that of an average comet. Several crude approximations have been made regarding several features. Among these are density in OH-cometary radicals;half-life of an H_2O molecule before photodissociation by solar radiation; and effect of the free oxygen atoms at 105 km. However, the main result appears probable: while the observation of the OH-radicals in an HW-daytime experiment appears very difficult, if not impossible, it would probably be possible in the twilight release of a smaller amount of water. Yet it seems that this amount should still be of the order of a ton;[5] it would be desirable to release the water at a higher altitude where the perturbing effect of the free oxygen atoms would be less pronounced.

It is difficult to predict the rotational intensity distribution in the (0-0) resonance band of OH, which would be excited by the solar radiation in an HW-experiment. Table 1 gives the OH-wavelengths measured in Comet 1959k and the estimated intensities in three comets (1941 I, 1948 I and 1959 k), which have different radial velocities (relative to the sun) and hence display different OH-profiles.

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[5]Since the expansion rate is rapid (order of 1 km/sec), the observation should be performed rapidly (scanning on a spectrometer; or with interference filter or monochrometer with photoelectric receiver). In the experiment by the Goddard Space Flight Center, 20 kgs of water were released from a Nike-Cajun rocket; for the spectroscopic detection of the OH-radicals this quantity is probably too small.

Table 1.--(0-0) Band of OH in three comets

λ	Intensities		
(1959k)	1941 I	1948 I	1959k
3078.7	2		7
79.8			2
81.6	1	1	7
86.4	2	3	7
90.6	4	5n	7
91.2			2
93.7	1	5	7
96.3	3	5	8
99.6	2	5	6

In a daytime HW-observation the emission is covered by the solar spectrum;[6] the profile of the latter may be found in the Göttingen Atlas. A few OH-lines coincide with strong Fraunhofer absorptions, and hence would appear more easily than other lines which fall in a complex region of the solar profile. As a first guide, one may assume that the strongest OH-lines appearing in an HW-experiment would be similar to those in a comet.[7] This is far from certain, since the duration of the HW-experiment is very short, and since the time between two successive absorptions of solar radiation by an OH-radical is longer than the HW-duration. Yet it seems reasonable to assume a fairly low rotational temperature for the OH-radicals; hence the region λ3079 - λ3100 will most probably contain the strongest OH-emissions in an HW-experiment.

All in all, it appears that the study of the OH-radicals in a twilight HW-experiment involving the release of approximately one ton of water at an altitude of a few hundred kilometers would be an interesting, yet delicate, experiment.

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[6] Even in a twilight experiment the ice crystals will cause scattering and reflection of the solar spectrum.

[7] Indeed, we made this assumption when comparing the surface brightness of the HW-cloud of OH and of the OH-cometary head.

What would the situation be, if the water were replaced by liquid ammonia? One fourth to one third would be released in the form of vapor (assuming that not much liquid was imprisoned in ice); the rest would freeze up. In the field of solar electromagnetic radiation, the photo-dissociation of NH_3 is faster than that of H_2O, maybe by one order of magnitude. Since a larger fraction of liquid NH_3 is released in the form of NH_3-vapor, and since the NH_3 molecule is more easily dissociated, it is likely that liquid NH_3 will be able to produce NH_2-radicals ten times as efficiently as H_2O produces OH-radicals. Moreover, the amount of solar energy which is available in the visual region (where the characteristic fluorescence spectrum of the NH_2-radicals may be excited) is much greater than near λ3090 (OH-emission). A twilight experiment on NH_3 may thus be successful with a release of liquid NH_3 much smaller (say by a factor of 10) than the required amount of water.

What would be the corresponding most characteristic emissions of NH_2? A comparison with comets is especially fruitful in this case. In comet 1956h the relative intensities of the transitions $(o, \nu_2', o) \rightarrow (o,o,o)$ of NH_2-emission are as follows (Fehrenbach, Haser, Swings and Woszczyk, 1957):

Table 2.--Relative intensities of the NH_2-emission bands in 1956h

ν_2'	Approximate λ of Q-branch	Strongest features in 1956h	Estimated intensity in 1956h
5	7350	$\cong$ 7350	1
6	6967	$\cong$ 6967	2
7	6621	6618.4	4
8	6299	6299.5	5
9	5977	5977.2	3
10	5703	$\cong$ 5703	2

In 1957d the relative intensities of the strongest NH_2-emissions were (J. L. Greenstein and C. Arpigny, 1962; A. Woszczyk, 1962)

Table 3.--Relative intensities of the strongest NH_2-emission in 1957d

ν_2'	Strongest feature		Estimated intensity	
	J.L.G. and C.A.	A. W.	J.L.G. and C.A.	A. W.
7	6619.11	18.03-19.10	3	9-8
	6640.73	40.75	3	7
8	6300.44	00.47	10	10
9	5976.69	76.68	6	8
10	5702.98	02.95	3	5
	5731.63	31.70	3	6

The most sensitive NH_2-emission is doubtless near λ6300. However, a difficulty may arise on account of the presence of the twilight flash of [OI], which has practically the same wavelength. The blending by [OI] may be determined by observing simultaneously the other component of the red [OI] doublet λ6363, or by observing the weaker NH_2-emission at λ5977.

On the whole, the NH_3-rocket experiment appears promising.

What would the situation be if ammonia were diluted in the water in an HW-experiment? It is probable that a 10-percent fraction of ammonia in water (by weight) would produce about the same intensity of fluorescent emission of NH_2-radicals as the fluorescent OH-emission. The observation of the NH_2-emission in daylight would, however, be difficult if not impossible.

It appears desirable to start with twilight experiments involving only one chemical compound, although even in this case several kinds of radicals may possibly be released. Eventually, experiments may be made with mixtures of compounds. If liquefied gases are used, they should then have similar boiling points, as is the case for NH_3(-33°C), C_3H_4(-23°C) and C_2N_2(-20°C). The other boiling points of the other possible parent molecules are either much lower (CH_4 : -161°C; C_2H_2 : -83°C) or higher (N_2H_4 : +113°C; HCN : +26°C; H_2O : +100°C; H_2O_2 : +152°C). In mixtures involving water there may be a formation of solid hydrates; these have been considered as possible constituents of the cometary nuclei (A. H. Delsemme and P. Swings, 1952).

The clouds should be observed from the ground, using telescopes equipped with cameras, polarimeters, photometers and spectrometers or narrow interference filters. Velocities of expansion of the radicals and variations of brightness as functions of time and distance from the point of release should be observed; photoelectric scans of the important spectral intervals of emission of the radicals (if possible for a determination of the rotational temperatures) should be made.

c) <u>Orbiting artificial cometary nucleus</u> - The interest of an orbiting artificial "Whipple nucleus" has been stressed on various occasions. The following is an excerpt from a report given in July, 1961 (P. Swings, 1962b).

> The theoretical mass loss rates from spheres of ices of H_2O, NH_3, CO_2, etc., by sublimation in vacuum, agree within a factor of approximately 10 at a heliocentric distance $r = 1$ a.u. These loss rates are sufficiently small so that an artificial icy conglomerate comet nucleus of about 1 ton could probably live for several days. A first artificial nucleus should probably be made of a single kind of ice, such as CO_2 or NH_3. Eventually, an artificial "Whipple nucleus" should be made of a mixture of ices of the probable parent molecules (H_2O, NH_3, CO_2) with an addition of meteoritic material. The density should be low, of the order of 0.1 to 0.5.[8] While it is fairly easy to estimate the mass loss rate for a sphere of pure H_2O ice, only a rough approximation can be estimated for a porous conglomerate of heterogeneous snows, with an addition of meteoritic particles and possibly solid hydrates.
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> This project has been discussed on various occasions with European colleagues in the course of the last year (1960), and suggested to the European Space Research Committee a few months ago. I understand that it has also been envisaged in the U. S., especially by Dr. B. Donn at the Goddard Space Flight Center of NASA. A one-ton orbiting artificial nucleus would probably release enough gaseous molecules to give rise to an observable artificial cometary head which could be studied spectroscopically and photometrically. Fairly long periods of observation are desirable, in order that spectrograms may be obtained; hence a 24-hour orbit would be preferred. Comparison of the spectra of the artificial and actual cometary heads would enable us to draw valuable conclusions on the chemical composition of real comets, and would provide clues for the preparation of subsequent experiments.
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> It would be useful to place various instruments orbiting together with the artificial nucleus, especially a mass spectrometer.

[8] This should probably be revised, a higher density being more probable.

I have learned recently that other experiments are contemplated, some of the "piggy-back" type, involving smaller masses of ice. Donn has prepared valuable reports on this matter.

Such experiments would help in understanding the physical phenomena involved in the production and evolution of cometary atmospheres and in the cometary bursts. The origin of the latter has been discussed in recent years by Whitney (1955), Haser (1955, 1956), Donn and Urey (1956, 1957) and Whipple (1961a). Whipple suggested that cometary outbursts may arise from a highly irregular deposition of matter in the nucleus, some extremely volatile material such as CH_4 being highly concentrated beneath a layer of some less volatile material, such as H_2O or NH_3, and producing an under-leaching process. As a matter of fact, it should be noted also that if the outer layers are at places very transparent, internal melting may take place, for example, in regions containing dust particles. A high vapor pressure may thus build up inside the nucleus if the melting region contains a volatile material. Eventually, critical conditions leading to an outburst may take place: a rupture occurs, and the liquid boils explosively.[9] Many experiments have been made in the past on the properties of ices (Tyndall, 1858; Bunsen, 1870; Burton and Oliver, 1935; Frank, 1949; Sears, 1956; etc.). However, new laboratory experiments more directly adapted to the cometary problem would still be welcome.

The orbiting artificial cometary nucleus should be observed photographically, photometrically and spectrographically from the ground.

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[9] At the time of the outbursts of Periodic Comet Schwassmann-Wachmann, which is always at a great heliocentric distance (of the order of 5 a.u.), the spectrum is purely solar. This means that the emissions of CN and C_3 (which fall in a favorable spectral region of the photographic emulsions used) are very much weaker than the scattered continuum. Nothing is known of the OH- and NH-emissions, which lie in the ultraviolet; CH is probably absent. This observation seems to indicate that the abundances of emitting radicals are very low. Of course, the probabilities of photodissociation of the parent molecules are 25 times lower than at $r = 1$ a.u. Hence there is probably not enough time to build up a sufficient abundance of radicals before the cloud expands to an unobservably low density in interplanetary space. As in the High Water experiment, the explosive release of matter from the nucleus is accompanied by a division of an appreciable fraction of the matter into small particles, ranging in size from a fraction of a micron to 100 μ. Such small crystals scatter the solar radiation efficiently.

d) Comet Probe - As for the Moon, Venus and Mars, the major breakthrough in our knowledge of the comets will result from comet probes. I shall consider here only the observations that may be carried in a fly-by experiment. Obviously, a direct sampling of the nucleus itself will eventually be required. Whipple (1961a) writes: "An enormous, if not definitive, insight concerning the nucleus and the evolutionary problems of comets could be gained by a space probe made to land on a cometary nucleus. Cores of the nucleus should be stratified like geological sedimentary strata and should give the oldest and least disturbed material record of ancient processes." Whipple (1961b) has also expressed interest in pacing the motion of a probe with the motion of a comet. However, the first comet probes should be designed for cometary observations at large relative velocities. All the main information on the cometary nucleus, head and tail will be gathered in one or a few hours; a system of storing the information transmitting it to the earth will be needed. The comet-earth distance may be shorter than the Venus-earth distance.

Obviously, the experiment should also be equipped to furnish information on space environment en route to and away from the comet. Valuable data could be obtained outside the plane of the ecliptic, especially by using a plasma detector (for measuring the "solar wind"), dust detectors and a magnetometer. As we shall later see such instruments would be needed in the neighborhood of the comet anyway.

We shall consider successively the nucleus and the coma and tail. A probe traversing the coma would at the same time have a good chance to traverse a part of the tail nearest to the nucleus.

(1) Nucleus - The general consensus favors Whipple's icy conglomerate model, but many questions remain unanswered. Is a cometary nucleus made of one bloc of ice, or of a few blocs, or of a multitude of relatively small solids (say a few meters in diameter)? What is the structure of the surface: fairly clean ices, or a mixture of ices and "dirt," or mainly meteoritic dirt? What are the size, shape and magnetic properties of the nucleus? What are the temperatures on the illuminated and dark sides?

a) Image-forming device - A small telescope, probably some kind of Cassegrain system, should produce and transmit images of the surface or of parts of it. The rotation of the nucleus may help in revealing different parts if the period is not very long relative to one hour. It would seem that a 15-cm or 20-cm telescope would be sufficient. At a distance of 100,000 km it would resolve objects about 1 km in size, and give a fair idea of the shape and size of the nucleus. Since the radius of the coma is of the order of 100,000 km the trajectory of the probe should have a miss definitely smaller than 100,000 km. Indeed (see "Coma," next section), in order to gain a real knowledge of the small solid particles of the coma, also of the parent molecules and radicals present only near the nucleus, a miss less than 10,000 kms is desirable.

b) Polarization and color of the nucleus - While a measurement of the polarization of the molecular emissions of the coma has no longer a marked interest (since the mechanism of fluorescence excitation has been overwhelmingly demonstrated), the situation is very different for the surface of the nucleus and for the scattering particles of the coma.

Measurements of the polarization of the light reflected by the nucleus should be made in different spectral regions. Similar observations would also give us the surface brightness at various locations on the nucleus and at specific wavelengths, including the infrared (hence the color indices).

c) Magnetic properties of the nucleus - Recent investigations have led to the hypothesis that certain molecular ionization phenomena take place in or near the nucleus. Moreover, magnetic effects have long been suspected in the tail. The relative brightnesses of the dust- and gas-tails in different comets may be closely related to the magnetic properties of the nuclei. A magnetometer having a sensitivity of the order of one gamma (10^{-5} gauss), which would measure the magnetic field in interplanetary space, en route to the comet, could provide valuable information on the magnetic field near the comet itself and in its atmosphere.

d) Infrared observations - Infrared receivers, possibly installed on a small telescope, should give us information on the surface temperature of the nucleus at various locations (illuminated and dark regions).

e) Radar observations - Information on the surface of the nucleus may be obtained by radar. I have no qualification to discuss this matter.

2) Coma and tail - The spectrum observed from the ground reveals only the molecules or ions that emit their resonance electronic transitions in the region 3000 A $< \lambda <$ about 1 μ; actually, very little is known beyond λ7000 A, except that the strongest bands of the red CN-systems are present in the coma. We cannot observe the gaseous components whose resonance systems are below λ3000 A; in particular, we have no observational evidence on the parent molecules. Possibly we shall gain information on the far-ultraviolet spectra, with the help of astronomical orbiting telescopes. However, the source of excitation -- the sun -- is weak in the ultraviolet. Moreover, the fluorescence excitation is strongly limited by the fact that the far-ultraviolet solar spectrum is essentially made up of discrete emissions. Perfect wavelength coincidences between a discrete solar emission line and a discrete absorption line of a cometary molecule do not take place frequently, and they are very sensitive to the radial velocities of the comet relative to the sun and of the different regions of the coma and tail relative to one another. More direct methods of physicochemical analysis should thus be used in addition to spectroscopy.

a) Far-ultraviolet spectrum - There is a possibility that the H_2 and several other cometary molecules may be revealed by their fluorescence spectra. These have been predicted recently (Swings, 1962b). Certain resonance series may be detected with ionization chambers and filters, without the need for spectrometers. An ultraviolet fluorescence of the solids nucleus and dust may also be revealed.

b) Densities - The total density would be measurable fairly reliably, with, for example, a Golay detector. I do not know whether mass spectrometry has been developed to the point that the partial abundances of the neutral molecules could be determined. The relative abundances of the ionized molecules may be measured by mass spectrometry. The total abundances of the ions and the electron densities may also be measured. We have practically no information on the continuous radio emission of comets: the measurement of plasma frequency would be interesting (I have no qualification to discuss this matter).

c) Magnetic field - This has been considered in section 1c.

d) Small solid particles - From the ground the only way to obtain information on the small scattering solid particles giving rise to the continuum of comets is by measurement of the spectral distribution of the intensity and polarization of the continuum at different phase angles. However, there are three unknowns: the natures (probably different kinds and mixtures), size distributions, and shapes of the particles. All three unknowns affect considerably the scattering properties. They are different in the head and tail, and may even differ in different comets, just as do the relative molecular abundances and the relative abundances of gas and dust (Swings, 1962a).

As much information as possible should be gathered by equipping the probe with instruments similar to those employed for the measurements of the particulate contents of space on satellites or sounding rockets.

Most convenient comets - (1) Periodic Comets - At all points of view except one (very low dust content) Encke's Periodic Comet is a very suitable periodic object. It has a short period of 3.3 years and a well-known orbit, so that it may be rediscovered long before perihelion passage, and observed regularly several months in advance (up to 10 months; about 6 months in 1964). Actually, an excellent provisional ephemeris computed by S. G. Makover, was distributed in March 1962; it covers the period from Jan. 6, 1964 ($r = 2.318$ a.u.; $\Delta = 2.587$ a.u.; $m_{vis.} \cong 19.0$) to September 12, 1964 ($r = 1.807$; $\Delta = 1.362$; $m_v \cong 16.0$). The closest approach of Encke's comet to the earth will be on July 13, 1964 ($\Delta = 0.328$). Many accurate observations of positions will be available several months before July 13, so that very precise data could be provided for the launching of the probe in March or April. The observation of the dust particles would be possible only if the probe approaches the nucleus within about 10,000 kms; this should be possible in 1967, probably even in 1964. There are several other suitable periodic comets.

(2) Unexpected Comets - Unexpected comets sometimes approach the earth even closer than Encke's comet. An unexpected comet may occasionally be discovered long before its closest geocentric approach. For example, Comet Arend-Roland (1956h) became very bright in the spring of 1957, after perihelion passage had been discovered many months before; its orbit was accurately known long before its closest geocentric approach. Could a comet probe be equipped in preparation for such an unexpected bright comet? Could it possibly be placed on a "parking" orbit?

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