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SCIENTIFIC POSSIBILITIES OF A SOLAR ELECTRIC POWERED RENDEZVOUS WITH COMET ENCKE

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INTRODUCTION

The present observational problem of understanding the nature and origin of comets is analogous to that we would face in attempting to understand a planet and its atmosphere if we possessed only data on its ionosphere and exosphere. Virtually everything we can observe remotely is a part of the rapidly escaping gas and dust atmosphere of the comet.

In situ studies of the coma and tails of a comet and their interactions with the interplanetary medium can readily be achieved by so-called fast ($V_{relative}$ > 5 km s^{-1}) flybys, as has been detailed in other papers at this colloquium. The flyby can also settle any lingering doubts about the reality of a compact nucleus in comets. Any pretense to real knowledge of the structure, composition, and activity of the comet itself, however, depends upon an ability to study the nucleus for some days at a range such that it fills a large solid angle as seen from the spacecraft. Studies of the mineralogical, chemical, and isotopic makeup of cometary solids, studies of great importance in solar system cosmology, can be made upon the dust flowing from it, but only if the relative velocity of the dust is sufficiently low to allow its capture, intact, for analysis. Details of the chemical and physical processes in the inner coma also are likely to remain poorly understood until given extended, careful study. These requirements define clearly the need for a true rendezvous with a cometary nucleus, an approach to a few tens of kilometers at essentially zero velocity for an extended period. This report summarizes the study of such a mission carried out at the Jet Propulsion Laboratory early in 1974.

MISSION ANALYSIS

The selection of target comets and the vehicles for their study have been the subject of numerous reports. In every such report P/Encke has been high on the target list, usually highest. Some of the reasons for this have been summarized by Atkins and Moore (1). The study reported here assumed a 1984 encounter with P/Encke, but it is equally applicable to a 1990 encounter, and the qualitative conclusions are applicable to other potential targets such as P/Temple 2 or P/d'Arrest. Unfortunately they are NOT applicable to P/Halley, rendezvous with that prestigous object requiring a swing-by of Jupiter and six to eight years flight time (2).

The only technology currently available which makes it possible to rendezvous with comets is solar electric propulsion. Rendezvous by means of a multiple impulse ballistic trajectory is possible in principle, but such a rendezvous with P/Encke, for example, requires 4-5 km s^{-1} of midcourse propulsion capability with propellants that can be stored for several years (3). No such hardware exists or is planned.

Trajectories for a solar electric propelled flight to rendezvous with P/Encke typically have aphelia of $2\frac{1}{2}$ to 4 AU and flight times of $2\frac{1}{2}$ to 3 years (4). Encounter was assumed to be 40 days before perihelion (at just under 1 AU heliocentric distance) in this study, although earlier rendezvous is possible. Scientific requirements, which follow, indicated a minimum period of 20 days near the nucleus was needed, and this presents no design difficulties. In fact it is believed that survival through perihelion is possible in a low-power, non-thrusting mode, with another period of 20 or more days of scientific study of the nucleus beginning about 20 days after perihelion.

The approach to the nucleus of an SEP spacecraft is a very gradual thing. The maximum acceleration that such a craft can develop is $\sim 4x10^{-4}$ ms^{-2}. The approach to the nucleus is roughly from the direction of the Sun in comet centered reference. In heliocentric reference, the spacecraft is nearer the Sun than the comet but moving toward it more slowly. The spacecraft accelerates to the same velocity as the comet just as the comet finally reaches the same heliocentric distance as the spacecraft. At no time is the spacecraft in the comet tail during approach, and since the available acceleration is so low, excursions into the tail are not practical unless the nucleus is to receive only cursory study. It was assumed in this study that in fact Encke's tail had been studied on a prior flyby and that the rendezvous would be devoted to study of the fundamental problems of the composition and structure of the nucleus itself.

Terminal guidance will be based upon information gained by optical imaging beginning at least 50 days before encounter. Two thousand kilometers from the nucleus an X-band radar will begin to furnish range and velocity information for the final day of approach. Closest approach might be $\sim$10 km at a relative velocity certainly <5 ms^{-1}. An ordinary radar altimeter would measure the velocity to 1-2 ms^{-1}. Coherent radar could reduce this to <0.1 ms^{-1}.

The mission strategy at this point becomes somewhat uncertain because of lack of knowledge of P/Encke itself. If Encke has a nominal mass of 10^{16}g attracting the spacecraft and an outflow of $2\pi x10^{27}$ molecules of H_2O per second repelling it, as implied by the measurements of Bertaux, et al. at 0.7 AU (5), then the net force should be attractive, and it might be possible to go into an orbit of some 5 days period. At best this would be a rather irregular orbit, since the gas flow must vary from day to night side of the nucleus and may be quite non-uniform even on the day side. Also the spacecraft cross-section presented to the outflowing gas will vary greatly, since the majority of that cross-section is solar panels which remain oriented toward the Sun. Certainly the spacecraft could be flown in a series of essentially linear trajectories past the nucleus, with a course reversal at the maximum acceptable range. It might even be possible to "hover" over the nucleus, if its mass is at least 10^{16} grams. (At 10^{16} grams the gravitational acceleration would be only $6.7x10^{-6}$ ms^{-2} at 10 km distance, but this is within the throttling capability of a single continuously operating solar electric thruster on a typical rendezvous spacecraft.) A closest approach of 10 km is certainly practical, as is some form of maneuvering designed to keep the spacecraft within a few hundred kilometers of the nucleus.

No landed probe was considered seriously in this study, primarily because of the obvious increase in cost it would entail. Such a probe could be built, but considerable delicacy of control might be needed to land it, since the escape velocity from the nucleus is probably about 1 ms^{-1}. In situ analysis or sample return were considered to be follow-on missions whose design (and even need) would be determined by the rendezvous flight.

SCIENTIFIC OBJECTIVES AND INSTRUMENTATION

The primary objective of the first comet rendezvous must be a detailed study of the structure, composition, and activity of the nucleus. The secondary objective is to understand the chemical and physical processes occurring in the icy halo or innermost coma, the region within 1000 km of the nucleus. Another objective may be additional study of the interaction of the comet with the solar wind as the spacecraft traverses the coma, assuming it can be made sufficiently electromagnetically quiet with the thrusters operating or that they can be turned-off at times.

Imaging

The primary information about the nucleus (size, shape, rotation, axial inclination, topography, spatial variation of albedo, color, photometric function, polarization) that can be obtained by means of remote sensing will come from the imaging system. The possibilities can best be illustrated by two systems. The existing Mariner 9 Camera B with 50 cm $f/2.35$ optics would offer a scale of 0.3m per pixel (picture element) at a distance of 10 km from the nuclear surface. At 0.7 AU heliocentric distance, unfiltered, there would be less than one picture element of smear for a signal to noise ratio of 50, even at 90^o phase for a reflectivity of only 2% at a transverse velocity of 4 ms^{-1}. Realistically, the imaging detector of choice in the mid-80's is unlikely to be the selenium vidicon (of Mariner 9 use). The most likely detector for use in that period is a charge-coupled device (CCD) having a 750x750 element array within a format 2.3x2.3 cm. With a 100 cm focal length $f/5$ telescope, the resolution on the nucleus would be the same as for the Mariner 9 system. In spite of the increased focal length at the same aperture, the CCD detector has enough sensitivity to give slightly less smear than the vidicon under the same conditions and has better linearity for improved photometric accuracy. It is also lighter, cheaper, and simpler. The CCD is therefore accepted as the probable flight instrument, but existing hardware could perform the mission.

Complete coverage of a 4 km diameter nucleus would require about 1000 exposures with either camera. The 1000 exposures could be taken one every 84 seconds (the standard cycle time of existing cameras) and transmitted in about 50 seconds with 8 bit per pixel encoding. Complete "photographic" coverage would be taken in one day in a hovering mode, if the nucleus rotates in about one day, with adequate communications available for the other scientific experiments without storing any data on tape. Since coverage in more than one color or polarization and at more than one phase angle is certainly desirable, and since several complete surveys to look for changes with heliocentric distance would be valuable, a minimum mission duration of about 20 days is needed.

Radar

Radar is absolutely necessary for at least one extremely important scientific purpose, namely scaling all of the observations. Radar is the best way to determine the distance from spacecraft to nucleus on a rendezvous mission. Besides range (and rate) data, the radar will measure the surface dielectric constant and the surface roughness. It may also make possible a mass determination as discussed separately. The radar could be designed to undertake other measurements such as detection of ejected debris and nuclear rotation, but it would be difficult to detect debris smaller than 20 cm, which is roughly the upper limit expected from Encke, or a rotation period slower than a few hours, so even limited complication probably is not warranted.

The system contemplated is an X-band radar transmitting peak power of 5 Kw (average power 5w) with a 50 cm antenna mounted on a scan platform with the other pointed instruments. This should permit simple detection of the nucleus at a range of about 2000 km. The signal to noise ratio would be 17 db at 500 km, which is probably the maximum distance from the nucleus that the spacecraft might attain after once having rendezvoused, no matter what maneuvering strategy is used.

Mass Determination

Mass is one structural parameter of great importance that is not easy to determine. A coherent radar can measure the radial velocity of the spacecraft relative to the comet to an accuracy better than 10^{-1} ms^{-1}. With the thrusters off, this would allow a measurement of the acceleration of gravity plus aerodynamic drag. The aerodynamic forces can be minimized by operating near the sunrise limb of the nucleus where evaporation of volatiles from the comet will be a minimum as will be the spacecraft cross-section as seen from the comet. (At sunrise the solar panels, which constitute 90% of the maximum spacecraft cross-section, are edge-on to the comet.) Perhaps the drag can be modeled and calibrated, if the flow field is not too irregular. At worst a lower limit to the mass can be determined. A possible complication is a nucleus of highly irregular shape.

The radar would be operated in a coherent mode only within about 50 km of the nucleus and only for the express purpose of mass determination. An extra electronic module weighing less than 5 kg and perhaps 15w of power would be the only requirements added to the standard radar.

No consideration was given to a gravity gradiometer because of the complications introduced by the complex non-gravitational forces. This possibility should be investigated further.

IR Radiometer

A quantitative understanding of the physical processes occurring on the surface of the nucleus will require several thermal maps of the nucleus at different heliocentric distances. Use of multiple spectral intervals is needed to provide the highest sensitivity over a range of temperatures and to measure the wavelength dependence of the emissivity of the nuclear material. The temperatures themselves are an important parameter in determining the exact nature of the surface activity, the energetics of the release of volatiles, as well as giving an indication of volatile composition. Temperature variation with phase angle and heliocentric distance will provide a measure of thermal inertia of the surface layer.

The Viking Infrared Thermal Mapper (IRTM) is suitable for this job virtually without change. A minor electronic change to allow for the possibility of higher temperatures than those expected on Mars is all that would be absolutely required, although new fabrication techniques giving lower mass would probably be utilized as well and are reflected in the summary table. This instrument would have a spatial resolution of 50m at a distance of 10 km from the surface. The spectral ranges are 0.3-3.0 μm, 6.0-8.0 μm, 8.0-9.5 μm, 9.5-13.0 μm, and 18.0-24.0 μm. The accuracy of measurements would be better than 1K for targets warmer than 150K, most of the uncertainty being in the radiometric calibration.

IR Spectrometer

Frozen condensates such as H_2O, CH_4, NH_3, CO_2, etc. have very characteristic reflection spectra in the near infrared. Although it is assumed that volatile composition will be well determined by mass spectrometry, the uniformity of their condensed phase distribution on the nuclear surface might well give important hints about the process by which that nucleus was formed. Further, should Encke exhibit some bare core, as Delsemme and Rud suggest may be the case (6), then these scans could be compared to the various asteroid and meteorite types. Therefore a filter wedge spectrometer is included in the instrument complement.

The instrument proposed here is a new design, though having features in common with the Nimbus 4 filter wedge spectrometer. An $f/3.5$ telescope of 15 cm aperture supplies energy to a continuously variable annular filter wedge. The filter is made in three pieces with three detectors, a PbS detector covering 0.6-3.0 μm, a

PbSe detector covering 3.0-3.5 μm, and a HgCdTe detector covering 3.4-6.0 μm. All are held at 180K by radiation cooling. The spectral resolution $\Delta\lambda/\lambda$ is about 1%. The field of view is 3 mrad, thus giving 30m resolution at 10 km. Under the worst possible assumptions of 2% reflectivity at 1.0 AU heliocentric distance, the signal to noise ratio is still 200 for a 10 second integration at 3.5 μm.

Mass Spectrometer

It is anticipated that a neutral mass spectrometer will still be one of the key experiments on the rendezvous mission. Although an earlier flyby also will have carried such an instrument, it is likely that any parent molecules or intermediate species with scale lengths less than 500 km or abundances less than 10^{-3} of water at best barely will have been detected. Many new parent species and most accurate abundances will remain to be determined. Since there is strong evidence for molecular and ionic interactions deep in cometary comae, it may also be desirable to operate for a time with the ionizing electron beam off to measure ambient ion densities in the inner coma.

Mass spectrometer operation during a rendezvous has many advantages. Relatively high gas densities and long integration times are most important. Days rather than seconds are available. Very near the nucleus, ions and radicals should be at a minimum, which will reduce instrumental interactions with the medium. There will be no molecular fragmentation from high velocity impacts. A rendezvous spacecraft has degassed in interplanetary space for almost three years. Xenon gas from the attitude control jets and mercury (fuel) and molybdenum (grid material) from the thrusters should cause no problem even if the spectrometer inlet is not perfectly "shadowed".

A double focusing magnetic sector type mass spectrometer, embodying an integrating electro-optical detector sampling all masses simultaneously, is recommended for the mission. A mass resolution of 100 over the mass range 1-100 amu is easily attained. It will certainly be possible to detect species present at a density of 100 cm^{-3}, and a 10% measurement of such a species could be made in a tenth of a day or less. This is an abundance only about 10^{-8} that of water at 10 km from the nucleus and 0.7 AU heliocentric distance. Ion sensitivities of 0.1 cm^{-3} are available.

Solids Analysis

A proper analysis of cometary solids is the most difficult experiment proposed here, but it could also prove the most valuable. If comets originate within the solar system, as there is increasing evidence may be the case (7,8,9), then cometary solids should be the least altered primitive solid material man is likely to have a chance to investigate which originated in the outer parts of the solar nebula. Obviously isotopic, chemical, and mineralogical analyses are all desireable.

Since the relative velocity of spacecraft and solids must be less than that of the outflowing cometary gas relative to the nucleus (a few hundred meters per second), several techniques appear feasible for capture of the solids, including mechanical trapping in foils and porous targets or by electrostatic trapping. Experimental work will be needed to define the best technique, taking into account the requirement that the captured material must then be transferred to the analytical apparatus.

For this mission it is suggested that the analyzer consist of a scanning electron microscope, an alpha-particle analyzer (including proton detectors), and an energy-dispersive X-ray analyzer. The X-rays for the last instrument would be produced by the electrons from the microscope and by the alphas from the α-particle instrument. These instruments in an integrated package will produce an elemental analysis of light and heavy elements at any point in the field of view, images of continuously variable magnification from 50x to 40,000x with great depth of field and an average analysis of all the collected material. Mineralogical identifications are routinely made from such data.

This complete analysis package remains to be developed. Commercial scanning electron microscopes are available in almost the size and weight needed, but these have never been packaged for spaceflight. X-ray and α-particle instruments have flown but not in the form needed. Since the first flight of this package probably is still 12-15 years in the future, an orderly development would seem no problem, but the development should not be put off too long.

Optical Particle Detector

The amount of non-volatile material in comets is known far less well than the volatile abundance. Abundance and size distribution of dust (smaller than $\sim$40 μm) can be estimated from the behavior of dust tails (10,11,12), but P/Encke itself has never exhibited a dust tail. The existence of larger debris can be inferred from radar observations of shower meteors associated with known comets (the β-Taurids with Encke), but it is not necessarily true that the average activity of many past apparitions as represented in the meteor stream is characteristic of activity today. Direct observations are needed. A satisfactory experiment can be expected on the precursor flyby, but it seems worthwhile to measure the solid particle flux over a period of time, both pre- and post-perihelion if possible, and to look for association of particles with particular areas of the nuclear surface, assuming the latter is not completely homogeneous. The priority of this experiment is lower than those described previously, however.

On a rendezvous mission, dust will be impacting the spacecraft continuously at very low velocity. While probably not directly damaging, some concern must be taken to maintain clean optical surfaces on several experiments, and direct measurement of the dust flux might even be associated with the required rate of "window washing". Model calculations indicate that the impact of larger particles (>1 mm) should be no greater than about one per hour per square meter, and some form of optical particle detector will be required to give good statistics.

The concept of remote optical detection of small particles was brought to fruition by Soberman and coworkers in "Sisyphus" (13). In principle "Sisyphus" can determine range, velocity, and the reflectivity-cross section product for each particle which moves into its field of view. Operational problems with the first flight units were not intrinsic to Soberman's basic idea, and practical units can be flown. Rejection filtering against the brightest cometary emission features can be used to reduce the background "noise" of the cometary environment. Looking away from the nucleus, a range to radius ratio of 10^5 should be practical, allowing detection of a 2 mm diameter particle at a distance of 100m or a 2 cm particle at 1 km. Detailed design and operational strategy of this instrument will depend heavily on prior experience gained in the fast flyby.

Magnetometer and Plasma Probe

As noted earlier, the rendezvous mission is designed to study the immediate environment of the nucleus. It will cross the shock front and contact surface (if such exist) on approach to the comet at relatively low velocity, however, 400m s^{-1} at $2x10^5$ km and 125m s^{-1} at $2x10^4$ km. This will offer an opportunity to map any relatively abrupt plasma discontinuities in more detail than can be achieved in a fast flyby at 8 to 26 km s^{-1} velocity. In fact, current models indicate a contact surface may only be 100 km from the nucleus of Encke, too close for a flyby to penetrate. Further, some comets have shown high amounts of ionization apparently extending virtually to the nucleus (14). While P/Encke is certainly no Comet Humason, some simple, reliable means of determining ion densities clear into the nucleus in search for anomalous (non-photo) ionization seems warranted, and where there is organized motion of ions there are fields. Finally, although it may appear that any intrinsic magnetic field associated with a cometary nucleus is improbable, an attempt to set a limit on such a field is not totally without merit, considering our lack of "real" knowledge of the nature of comets. Type I carbonaceous chondrites are magnetic.

A magnetometer and a plasma probe offer simple, reliable measurements of field strength and ion density for a relatively modest mass allotment. Both instruments may be limited to some extent by having to function on an operating solar electric propelled vehicle. It probably will not be practical to go below a field strength stability of ±0.1γ with a mast of practical length carrying the magnetometer. Ions near the lower end of the plasma probe's 5 ev - 3 kev range may have their paths deviated by the thruster plume, although the spacecraft remains electrically neutral. This will be particularly true when the plume directly opposes the plasma flow. In the event that something interesting is found, it would be possible to turn off the thrusters for a few hours, of course. While additional instruments might prove useful, we felt their inclusion to be an unwarranted expenditure of mass and money on this second generation mission designed primarily for study of the cometary nucleus. Information from the precursor flyby could easily change this conclusion.

CONCLUSIONS

We have considered the minimum scientific instrumentation likely to result in as complete an understanding of the composition, structure, and activity of a cometary nucleus as is possible without landing on it. That payload is summarized in Table I. The payload will also give useful results on secondary goals of a better understanding of physical processes in the inner and outer coma. Studies of composition, by means of an actual landing on the surface, details of the internal structure of the nucleus, and sample return were considered beyond the scope of this mission.

Table I. Summary of a Baseline Payload for P/Encke Rendezvous

Instrument	Weight (kg)	Power (watts)
Imaging	18	15
Radar	10.5	average 45
Coherent Radar	5*	15*
IR Radiometer	9.3	average 10.5
IR Spectrometer	9	6
Mass Spectrometer	5.3	10
Solids Analysis Package	20 ?	50 ?
Optical Particle Detector	5	3
Magnetometer	2+	3
Plasma Probe	5	6
	89.1	163.5

* requirements in addition to those listed under Radar, if there is to be a nuclear mass determination

+ not including weight of the mast

The payload of Table I seems well within the capability of a solar electric propulsion system in the 15-20 kw (at 1 AU) class (4), and there is no other obvious solution to the problem of its delivery. The material presented here is a brief summary of one aspect of cometary mission studies undertaken by the authors and other staff members of the Jet Propulsion Laboratory during the past two years. We hope that this work will help to provide a better understanding of the great scientific potential of a rendezvous mission in the field of cometary studies.

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DISCUSSION

J. C. Brandt: Can we afford the "grandiose" mission you have presented?

R. L. Newburn: I think we can afford it, if we can afford a space program. I think this is important enough in the time frame we are now considering that yes, we can now afford it.

W. F. Huebner: If large refractory grains are expected in the coma of Encke, then snow-grains will also be present which make seeing very difficult.

R. L. Newburn: We may get a good mass determination for the small material coming off by noting how often we have to operate our windshield washers on the imaging system.

M. Mumma: Wells et al., have studied the 'blizzard' problem for the 1980 flyby missions of Comet Encke. They found that the Mie-scattered sunlight from dust in the field-of-view was ~ 3 orders of magnitude fainter than the nuclear surface brightness. The scattering by ice particles was found to be at worst equal to the dust brightness. They concluded that the ratio of nuclear brightness to background brightness was at $\gtrsim 100/1$, hence 'blizzard' would not adversely affect the imagery experiment.

C. Cosmovici: Did you consider the opportunity to guide the spacecraft to an asteroid after a flyby or a rendezvous mission?

R. L. Newburn: I do not know of any studies that have been made for the post-encounter trajectory, but one or two asteroids can be flown-by on the pre-encounter trajectory. This is because a very slow encounter requires a trajectory that takes you well into the asteroid belt on the way to the encounter with the comet.

D. Bender: In answer to the possibility of asteroid encounters on a comet mission one must allow 200-300 day intervals between the encounters because of the trajectory changes required. On the Encke Rendezvous Mission (~ 960 days) two asteroid encounters are possible. The flyby speeds are 10-15 km/s.