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A SURVEY OF COMET MISSIONS

JAMES B. EADES, JR.

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GODDARD SPACE FLIGHT CENTER
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Presented to the
Special Projects Branch VI Astrodynamics Conference
November 7 and 8, 1967, Goddard Space Flight Center
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ABSTRACT

A discussion of comets and the possibility of scientific missions to these bodies, as they pass through the solar system, is presented. Mention is made of the probable experimental devices needed to accomplish these missions; the candidate comets (through 1986) are noted and discussed in regards to the requirements needed for each flight operation.

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The basic reasons for undertaking scientific explorations in space are to provide information about the solar system, the environment surrounding the celestial bodies—and to assure the eventual success of manned expeditions. Considering the numbers of objects found in space—after the artificial satellites and other remnants of hardware—comets comprise the largest group of bodies which make occasional excursions into the near solar regions. Consequently, they provide a ready opportunity for scientific investigation.

It should be evident that comets have enjoyed a rather notorious and awesome past. They have afford mankind with spectacular celestial displays for centuries; they have been viewed with terror, and feared as the forerunners of impending disasters. In addition, cometary sightings often have coincided with prominent historical events—for instance, sightings were recorded at the times of—

(a) the Jewish revolt in 66 AD;

(b) just prior to the last great battle between Atilla the Hun and the Romans in 451;

(c) just before William the Conqueror defeated King Harold (and his Saxons) at Hastings in 1066;

(d) and, a comet was seen a short time before a minor sailing event in 1492.

As an example of the superstition associated with comets—in 1910 the Haitian natives purchased "pills" to ward off sickness which they feared would result from a "poisoning" to be brought on by having the tail of Comet Halley brush the earth as it passed.

To the present time there have been approximately 900 comet sightings recorded. These represent some 8 new apparitions each year—about one-half of which are new comets. Also, from this total number there will be, on the average, one spectacular sighting each decade; i.e. an appearance which will provide a truly magnificent celestial display.

One is reminded that major comets typically have tails which are some 10^6 km long—these can extend over an arc of approximately 90°; or, can be referred to as being a length of some 40 "fuss"!

The spectacular displays are generally produced by the "new" comets; those which come into the solar regions from far out in space. They have not been subjected to previous or repeated solar passages, hence their constituents have not been "boiled-off" through interactions with solar radiation.

It is the belief of many investigators that a study of the minor bodies (the asteroids, meteors and comets) in concert with the major celestial objects, will contribute immeasurably to our basic understanding of the solar system. As a matter of fact it has been suggested that comets probably consist of rather primative (or, primordal) material—remnants of the earliest age of the solar system; or alternately, that they may be composed of material which is to be found in the near regions of "far space".

Actually, it is the formation of a comet which is one of the major questions in need of an answer. One theory proposed that these objects can be described as "giant, dirty snowballs", this would be a modification of the Whipple icy-conglomerate model; while another suggests that they may be composed of a swarm of particles held together by their own gravitational attraction.

There are numerous hypotheses regarding the formation of comets. For instance:

(1) Stromgren asserts that comets are, and always have been, a part of the solar system;

(2) while Orlov (1958) says that they are continually being formed, within the solar system, by such actions as the collision between asteroids and meteors.

(3) Another theory (Oort, 1950) presumes that their formation is by the explosion of a planet-type body which deposited a sphere of comet material around the solar system; and

(4) Carlin (1938), Lyttleton, (1953) say that comets were acquired recently from interstellar clouds outside of the solar system itself.

If there is anything at all which we do know about comets, it is that they are completely different in makeup from the earth; and, that they are probably among the most interesting bodies (scientifically) which are to be found in our galaxy.

The Space Science Board of the National Academy of Sciences has developed a rationale for the exploration of the solar system. Within this one finds a statement to the effect that studies related to the origin and evolution of the Earth, Sun and Planets (including the minor bodies) are to be undertaken. Certainly, in order to satisfy these intentions it will be necessary to undertake the scientific exploration of space. It should be evident that in its fullest extent this program cannot be realized until there has been a study and analysis of samples taken from the various objects found in the solar system.

When attempting to apply these edicts to cometary objects a number of questions naturally arise; categorically these fall into two groups:

(1) those which have to do with the physics and the composition of comets; and,

(2) a second group which has to do with the interactions between the comet's material, solar corpuscular and electromagnetic radiation, and with the interplanetary magnetic fields.

The instrumentation needed to investigate the comet and its features, will involve the following items:

(1) Photo-imagining devices (t.v. cameras, to study features of the comet, its head and tail).

(2) Mass spectrometers (to measure the chemical status of gases in the coma and the tail).

(3) Solar particle detectors (to determine the distribution, mass and velocity of the solid particles in the comet and its tail).

(4) Magnetic detectors (Magnetometers) (to examine the magnetic field of the comet, and the field intensity in space).

(5) Plasma spectrometer (to examine plasma streams at the comet, and to study interactions between the comet and its environment).

and some means for

(6) Mass Determination (No instrument prescribed, as such; these are not presently available).

It is expected that the information gathered during a cometary encounter would aid in verifying and/or rejecting the various theories concerning comets.

Hopefully this information might also lead to a better understanding of their origin, and aid in providing answers to such questions as whether or not comets are truly members of the solar system.

There is also a need to verify and explain some of the unusual occurrences which have been noted from the viewing of comets. For instance, during active periods some comets appear to have "jets" or fountain-like eruptions issuing from the sun-lit nucleus; this may be the process by which tails are formed. Recently this phenomenon was reported and discussed in a proposed paper (see Rahe,[(1)*] 1967); the author comments that this feature is difficult to see and not at all regular and continuous in its occurence. No comments were offered in explanation of this phenomenon.

In part, it is the inability of scientists to fully examine comets from earth, to verify theories relative to their origin and evolution, and to better describe their features which signifies the need for scientific explorations. Naturally such a requirement points to the utilization of one of our most recently acquired scientific tools — the space probe.

COMET MISSIONS

Presuming, as fact, that there is a need for comet missions the next step is to examine this situation and to define the constraints which must be met. With these restrictions described we should next examine the comet catalogues and decide on the most likely candidates! Certainly it is desirous to select only those members of this group which are most likely to assure success in any proposed mission. It should be evident that the constraints which will be imposed are not absolute; that is, trade-offs will have to be undertaken, and each mission will probably be considered on its own merits.

Some of the constraints which have been imposed are related to the following:

1) The launch vehicle.
2) The intercept Miss Distance; this refers to the "passing" distance from the nucleus.
3) The need to intercept the comet near perihelion; for maximum observability of the cometary phenomenon.
4) Visibility of the comet from Earth (during intercept).

*Superscripts refer to references cited at the end of this paper.

5) The relative speed between the Comet and the Spacecraft at intercept; and

6) the expected spacecraft hazards.

Of necessity, only periodic comets should be considered; and, only those which have had at least two prior apparitions. Considering all of these constraints, the ones most affecting the success of a mission encounter are: the miss distance, visibility from earth, and the relative speed at intercept. The remaining restrictions are important, but not from the same point of view. In particular the visibility aspect of the mission, and the closing speed are the factors most significant to the selection of candidate comets, per se.

After having given due consideration to these constraints and inspecting some 30 likely comets (up through 1986 expected apparitions) those which were selected are noted in the table shown below, (Table 1).

COMETS - 1969 THROUGH 1986

These are the comets which are deemed as best suited to meet the criteria outlined earlier (there are 10 missions shown for 7 comets).

In the first colum are the candidate comets—

(A) The dates for launching (L/V) are shown in 2nd column.

(B) All vehicles are launched after acquisition except for the comets Giacobini-Zinner and Tuttle-Giacobini-Kresak.

(C) Next is the date of perihelion passage; it is interesting to find that generally the pericenter radii are greater than 1.0 AU, except for Comet P/Encke ($r \simeq .34$) and Comet P/Halley ($r \simeq .59$).

(D) Intercept occurs after perihelion passage except for Comet P/Tuttle-Giacobini-Kresak.

(E) The date of intercept is noted next; the trajectory types are generally Type I ($\theta \leq \pi$ rad), however, Type II trajectories are flown for comets Giacobini-Zinner, Encke (long duration flight), and Halley.

(F) Vis-viva integral value is included in the table, as is the approach speed; these are to indicate the relative energy expenditures needed to accomplish the various missions.

(G) The next column indicates the relative speed of the spacecraft (to the comet) at intercept.

Table 1

Spacecraft Trajectory Data for Comet Missions

Comet	Launch Date	Launch After Acquis.	Perihelion Date	Encounter Date	C_3 $(km/sec)^2$	Approach Speed (km/sec)	Time of Flight (Days)	Commun. Distance (AU)
Pons-Winnecke	12/27/69	Yes	7/19/70	7/27/70	4.3	14.6	182-212	0.635
Kopff	1/23/70	Yes	10/04/70	11/01/70	22.3	10.8	270-282	2.11
Giacobini-Zinner	10/16/71	No	8/03/72	8/09/72	5.2	22.2	268-298	~1.0
Tuttle-Giacobini-Kresak	9/11/72	No	5/28/73	4/17/73	8.66	13.2	188-218	0.83
Encke	9/13/72 2/07/74	Yes	4/28/74	6/10/74	6.2 13.0	28 35-38	240-270 80-110	~0.39
D'Arrest	4/21/76	Yes	8/13/76	8/13/76	2.3	13	100-130	0.18
Kopff	2/26/83	Yes	8/18/83	9/02/83	4.2	8	175-190	1.0
Halley (direct)	2/08/85	Yes	2/05/86	3/17/86	4.0	69	210	1.25

(H) The duration of flight is noted in the next column. The time span is (generally) indicative of the launch window selection. One exception to this occurs for Comet P/Kopff which has a near ecliptic plane-of-motion itself. This mission may be flown to intercept at almost any point of interest.

(I) The communications distances are normally less than one AU (as desired by criteria). There is a real need to keep this value as small as practicable in order to reduce the power requirements, and to enhance transmission rates.

(J) In almost all cases intercept occurs at the descending node (except for Comet Tuttle-Giacobini-Kresak), and at a heliocentric distance in excess of one AU. Comets Encke and Halley are the exceptions, as expected.

(K) The one comet in this group, not having direct motion is P/Halley! Its inclination is approximately 162 degrees.

The missions noted, here, have launch speed requirements ranging from (roughly) 11.5 to 15.5 km/sec.; the approach speeds are as low as 8 km/sec (P/Kopff, 1983) and as large as 69 km/sec (P/Halley, 1986).

The low approach speed makes Comet P/Kopff ideal—or best suited—for an attempted rendezvous and speed matching maneuver. In providing for this extra ΔV requirement it is found that (ideally) the launch vehicle must carry aloft a spacecraft whose weight is increased more than 10 fold when compared to the simple intercept case. Needless to say, if an attempt is made to match the speed of some one or more of the other comets shown here, the mission would require a launch vehicle equivalent to the Saturn V; and this to carry aloft a scientific spacecraft and instrument payload weighing approximately 500 pounds.

One of the most critical factors involved here is the accuracy to which comet orbital elements are known. How well these are known, before vehicle launching, will markedly influence the number of corrective maneuvers needed later, and the size of each such maneuver. Hopefully these missions could be flown with no more than 3 such corrections (1 post-launch maneuver, to correct initial launch errors; a mid-course correction; and a final, pre-intercept correction, applied to insure the proper intercept distance of from 1000 to 2000 km.).

OTHER METHODS—MANEUVERS AND OPERATIONS

It should be mentioned that the missions just discussed were developed using velocity impulses. It is likely that some savings in mass ratio can be had if the intercept maneuvers are accomplished by means of continuous thrustin operations. Obviously, for maximum benefit, it would be necessary to program the thrust direction so that optimum savings are achieved. If the levels of thrust are not large then this situation could be treated as if micro-thrusters and/or solar sailing techniques were used to achieve the desired transfers. If the mission is considered as one using solar sailing, then the effect of the "solar wind" should be included.

These trajectories, produced by continuous thrusting, should be compared with those previously defined in order to develop a most economically feasible mode of operation.

The trajectories previously discussed intercepted the comets in the plane of the ecliptic. For some situations it may be necessary to suffer the consequences and join the comet in its own plane of motion. Missions of this design are in need of additional study to ascertain the penalties which would arise from this operation.

Michielsen[2] (1967) has described two missions for an encounter with Comet Halley (1986) wherein the spacecraft is launched with direct motion, then turned around so that at intercept both bodies are traveling with retrograde (heliocentric) motion.

The first operation consists of a "turn around" maneuver at the apogee of a Hohmann-like transfer. It is found that this flight has an overall cost in ΔV of (approx.) 22 km/sec from earth's orbit—or 31 km/sec from liftoff! The flight time involved here would be between 7 and 8 years, with the apocenter for the maneuver being at 7 AU.

As an alternate mode of operation—one taking advantage of the massive planet Jupiter—a swing-by maneuver was developed for two consecutive launching dates, one year apart.

It should be noted that by passing ahead of Jupiter the spacecraft would give up energy to the planet but would achieve the needed turning of its trajectory. The advantage of such a maneuver is that it reduces the overall velocity requirement for the operation; in this case the ΔV would be reduced by (approx.) 6.5 km/sec, the total ΔV would be 24.5 km/sec from lift-off, or 15.5 km/sec from earth's heliocentric orbit. The flight time for these maneuvers (to intercept), however, is between 7 and 8 years in duration.

Alternately, a similar flight operation has been developed using Saturn, as the swing-by planet, to deflect the trajectory. A saving in required velocity input is also achieved here, but at the expense of increased flight duration; e.g. the overall lapsed time is nearly 12 years.

From a practical point of view these missions have some obvious drawbacks!

Turning again to the continous thrust operations, an alternate suggestion would be to attempt the turn around maneuver by means of a minor circle turn. This is a maneuver occurring in a target plane (which is normal to the plane of earth's heliocentric motion). It is not evident that drastic savings in mass ratio, or time of flight, can be realized by this mode of operation; however, combined operations—including a swing-by maneuver—may produce a more acceptable solution for retrograde comet approaches. It should be mentioned that there are seven known periodic comets having retrograde motion.

Time does not permit a discussion of the pros and cons of the case for using continuous thrusters, those such as thermo-nuclear and electric propulsion systems. It will be sufficient to say that these devices are not well enough developed at this time to be considered as replacements for chemical systems.

In order to fly missions requiring large velocity increments it will be necessary to use large boosters in the Jupiter and/or Saturn class.

Contrary to this, it can be shown that the requirements for intercepting periodic comets, having direction motion, can be met by present day booster systems. Of course, maximum utilization can be achieved only by the judicious selection of the upper stage rockets.

In summary, then, it can be said that missions to comets are feasible, practical and of potentially significant scientific value. Present day spacecraft and launch vehicles are adequate for these operations if direct fly-by trajectories are contemplated. At present only a limited number of comet rendezvous missions should be considered unless the largest classes of boosters are to be employed. Long range missions such as the intercept of Halley's comet in its retro-motion are possible, but will require extensive flight durations and large velocity inputs.

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