THE SELECTION OF COMETS FOR FUTURE SPACE MISSIONS

D.K. Yeomans
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109
U.S.A.

ABSTRACT. The criteria used to select a short period comet for possible future rendezvous space missions are stated and the selection process is outlined. For the time period 1900 - 2000, several candidate comets offer opportunities for spacecraft rendezvous. Two of the best candidates are periodic comets Kopff and Wild 2.

1. INTRODUCTION

The scientific objectives of future space missions to comets are generally agreed upon (NAS-ESF, 1983). These objectives include the following:

1. Determine the chemical composition and physical structure of the comet's nucleus and characterize the nucleus as a function of heliocentric distance.
2. Characterize the coma through the identification of parent molecules and the processes by which these molecules are transformed in the inner coma and observe the changes in coma activity as a function of time and heliocentric distance.
3. Determine the composition and distribution of coma grains and study their interactions with the coma plasma.
4. Study the interaction of the cometary plasma with the solar wind.

The International efforts underway to study comets Halley and Giacobini-Zinner from flyby spacecraft will go a long way in addressing the above scientific objectives (Reinhard,1982). Following its last lunar swingby in December 1983, the International Cometary Explorer (ICE) spacecraft was targetted toward a September 11, 1985 flyby of periodic comet Giacobini-Zinner. This spacecraft, with its complement of plasma instruments, will fly through the ion tail of this comet and hence concentrate on the fourth scientific objective listed above. The ability to redirect an earth orbital spacecraft (whose major mission goals had already been attained) to fly by one of the very few short period comets with a visible ion tail was a fortunate circumstance. There are plans for a flotilla of five spacecraft to fly by comet Halley during the interval March 6-14, 1986. The Soviet Union will send the first of its two VEGA

A. Carusi and G. B. Valsecchi (eds.), Dynamics of Comets: Their Origin and Evolution, 415–421.

https://doi.org/10.1017/S0252921100084104 Published online by Cambridge University Press

spacecraft past Halley on March 6 at a distance of 10,000 km on the sunward side. The second identical VEGA spacecraft will follow in a similar flyby trajectory on March 9. The Japanese spacecraft, Planet A and MS-T5 will pass closest to comet Halley on March 8 at a distance larger than 100,000 km. The European Space Agency's Giotto spacecraft will fly through Halley's inner coma (< 1000 km sunside) around midnight (G.M.T.) on March 13. The extraordinary interest in space observations of comet Halley is understandable when one realizes that this comet is the only one displaying the full range of cometary phenomena and having a predictable orbital path. When taken together with the coordination of ground based observations by The International Halley Watch, the space observations of comets Halley and Giacobini-Zinner should address many of the scientific objectives for cometary missions.

While the scientific return from the various planned flyby missions to comets Halley and Giacobini-Zinner will return a vast amount of valuable data on the tail plasma and the coma's gas and dust components, the primary scientific objective (to study the nucleus) will only be addressed in a preliminary fashion. An intensive study of a comet's nucleus will require a space mission to rendezvous or fly alongside a comet for a period of time, to orbit the nucleus itself and to study its chemical composition and structure over a far longer time than is afforded by a fast flyby space mission. The remainder of this paper will discuss the target selection process that has been undertaken for future rendezvous missions to comets.

2. TARGET SELECTION CRITERIA FOR COMET RENDEZVOUS MISSIONS

In selecting a group of comets that are attractive candidates for a future rendezvous mission, the following criteria were used;

1. The target comet's orbital motion should be well understood.
2. The comet should exhibit both quiescent and active stages and it should be possible to rendezvous with the comet well before it becomes active.
3. Near perihelion, the comet should have a relatively high gas production rate.
4. A good observational history should exist for each comet.
5. During the rendezvous phase of the mission, the comet should be easily observable from the ground.
6. The orbit of the target comet should be such that it does not place unnecessary cost burdens upon the launch vehicle, spacecraft or ground operations.

An obvious criterion for a rendezvous target comet is that its orbital motion be well understood. There have been cases where periodic comets have poorly known orbital motions (ie. comet Westphal) so that the spacecraft navigation to the comet would be quite difficult, if not impossible. For this same reason, one apparition comets are a poor choice despite the fact that they are often the most active comets. In general, three apparitions of a comet are necessary before a comet's orbit becomes well known (Marsden, 1968).

The study of the target comet's nucleus is the primary scientific objective, and since the nucleus should be observed evolving from its inactive to active phases, the target comet should have both a quiescent and active phase. Very close measurements of a comet's nucleus are required to satisfy the scientific objectives so that these most important observations should be made first and when the comet's dust and gas environment is least hostile - when the comet is inactive. In addition, the navigation of a spacecraft in orbit about a comet's nucleus will require a knowledge of the mass of the nucleus and a mass determination derived from Doppler tracking data is most easily effected in the absence of gas and dust drag forces acting upon the spacecraft (Yeomans et al, 1980).

In order to study the parent and daughter species in the cometary coma, the spacecraft instruments must be supplied with a sufficiently dense gas and dust environment to make meaningful measurements. Hence the target comet should be relatively active near perihelion. In Table I, candidate comets are listed in order of their maximum magnitude which is usually the comet's apparent magnitude at perihelion (reduced to 1 AU from the earth). M. Festou has shown that the comet's maximum magnitude is a good indicator of the comet's maximum gas production rate (NAS-ESF, 1983).

Each candidate comet should have a fairly good history of observations so that environmental gas and dust models can be prepared for the comet. These models are necessary for determining instrument sensitivity requirements and the requirements for shielding against dust and electromagnetic radiation.

For each candidate comet listed in Table I, the most current orbit has been integrated forward to determine the times of perihelion passage in the 1990-2000 period. Full planetary and nongravitational perturbations were taken into account at each time step and an ephemeris was generated for extended intervals on either side of perihelion. In most cases, the initial conditions were taken from the catalog of B.G. Marsden (1982). All those comets listed in Table I have good ground based viewing opportunities surrounding at least one of the perihelion passages. Good ground based viewing conditions during the rendezvous phase of the cometary mission will allow the correlation of close up spacecraft measurements of the nucleus and inner coma with the ground based observations of the outer coma regions. The combination of these two data sets will allow the total science return to be larger than the sum of the individual efforts.

In Table I, each candidate comet is listed in order of its maximum visual magnitude, reduced to one AU from the earth. Comet Halley is included for comparison. The perihelion distance(q), orbital inclination(I) and number of observed apparitions are then given followed by future perihelion passage times and the ground based viewing opportunities on either side of the given perihelion. Those periodic comets that do not have good ground based viewing near their perihelion passages in the 1990-2000 interval are not included nor are those comets whose maximum magnitude gets no brighter than 12. The comets listed in Table I satisfy the first five of the six selection criteria. For comets in highly inclined orbits (I >25 degrees), the energy requirements for a rendezvous spacecraft are prohibitive. Ideally, the rendezvous comet target should have a low inclination so that major orbital plane changes in the spacecraft trajectory are not necessary. Hence, comets with large inclinations such as Borrelly and Giacobini-Zinner were not given further consideration. The most attractive opportunities for a comet rendezvous mission are given below. These comets and their perihelion times of interest are given in order of their maximum brightness.

Encke (May 1997)
Kopff (July 1996)
Wild 2 (May 1997)
Honda-Mrkos-Pajdusakova (Dec. 1995)
d'Arrest (July 1995)
Tempel 2 (Sept. 1999)
Tempel 1 (July 1994)
Churyumov-Gerasimenko (Jan. 1996)
Tuttle-Giacobini-Kresak (July 1995)

It should be noted that the 1997 apparition of comet Encke is only fair in terms of ground based viewing opportunities and comet Wild 2 has only been observed at two apparitions to date. However, because of its relatively high gas production rate, Wild 2 has been retained as a possible mission target. During a recent study, the above list of comets was studied in light of their ease of access for a rendezvous spacecraft (Yen, 1983). Comet Tempel 1 was not considered because it would have required a launch date considered to be too early for current advanced mission planning. The current injected spacecraft mass was assumed to be 2787 kg, the launch vehicle was assumed to be NASA's space shuttle with a Centaur G' booster and the arrival of the spacecraft at the comet was constrained to be at least 100 days prior to perihelion. Opportunities to fly by one or two asteroids enroute to the comet rendezvous were also considered important in the final selection process. Preliminary studies soon indicated that the shuttle launch capability was inadequate for effecting a rendezvous with comet Encke (during its 1997 apparition) and comet d'Arrest (during its 1995 apparition). The field of acceptable target candidates was then reduced to Kopff(1996), Wild 2(1997), Honda-Mrkos-Pajdusakova(1995), Tempel 2(1999), Churyumov-Gerasimenko(1996) and Tuttle-Giacobini-Kresak(1995). Additional studies were then conducted on these six comets in an effort to determine their relative merits for future rendezvous missions (Yen, 1984). Of these six comets, comet Kopff is the brightest one near perihelion and hence the most physically attractive rendezvous target.

Under the stated assumptions, Table II presents the rendezvous opportunities for the three comets of most interest for a comet rendezvous mission in the mid 1990's. After each comet's name is given the perihelion passage time (T), the arrival date(AD) given in number of days before perihelion, the first day of the launch period (LD), the flight time to the comet in years for an optimum ballistic trajectory (FTC), the flight time, from the earth, until both the comet and spacecraft reach perihelion (FTP), the launch energy required (C3), the Shuttle/Centaur G'

TABLE I: Potential Targets For A Comet Rendezvous Mission

Comet	Last Apparition	Max. Mag.	q (AU	I (Deg.)	No. of Appar.	Perihelion Passage	Grd. Based Viewing
Halley	1982i	3.0	0.59	162	29	1986 Feb. 9	Fair
Encke	1980XI	7.1	0.33	12	52	1987 Jul.17	Poor
						1990 Oct.28	Good
						1994 Feb. 9	Good
						1997 May 23	Fair
						2000 Sep.29	Poor
Kopff	1982k	8.2	1.58	5	12	1983 Aug.10	Exc.
						1990 Jan.20	Poor
						1996 Jul. 2	Exc.
Wild 2	1983s	9.1	1.49	3	2	1984 Aug.20	Poor
		9.4	1.58			1990 Dec.17	Good
		9.4	1.58			1997 May 7	Exc.
Honda-Mrkos-Pajdusak.	1980I	9.3	0.54	4	6	1985 May 24	Poor
						1990 Sep.13	Exc.
						1995 Dec.26	Exc.
d'Arrest	1982VII	9.3	1.29	19	14	1982 Sep.14	Exc.
						1989 Feb. 4	Poor
						1995 Jul.27	Exc.
Tempel 2	1982d	9.7	1.38	12	17	1983 Jun. 1	Good
		10.0	1.48			1988 Sep.17	Good
		10.0	1.48			1994 Mar.17	Poor
		10.0	1.48			1999 Sep. 8	Good
Tempel 1	1982j	10.9	1.49	11	7	1983 Jul.10	Exc.
			1.50			1989 Jan. 4	Poor
			1.49			1994 Jul. 3	Exc.
Churyumov-Gerasimenko	1982VIII	11.1	1.30	7	3	1982 Nov.12	Exc.
						1989 Jun.19	Poor
						1996 Jan.18	Exc.
Tuttle-Giacobini-Kresak	1978XXV	11.2	1.12	10	6	1984 Aug.28	Fair
		11.1	1.07			1990 Feb. 8	Good
		11.1	1.06			1995 Jul.29	Fair

https://doi.org/10.1017/S0252921100084104 Published online by Cambridge University Press

injected mass maximum (Mo), the post launch delta V required to acomplish rendezvous (ΔVPL1), and the delta V remaining for enroute asteroid flybys and post rendezvous operations of the spacecraft around the comet itself (ΔVPL2). From Table II, it appears that the fuel supply (ΔVPL2) for asteroid flybys and post rendezvous maneuvers is marginal for comet Honda-Mrkos-Pajdusakova. Clearly the comet Kopff 1996 opportunity is the most desirable in terms of available fuel at rendezvous and arrival time at the comet. Although without a long history of observations, comet Wild 2, during its 1997 apparition, is also attractive in terms of the ease of spacecraft rendezvous.

TABLE II: Comet Rendezvous Mission Parameters

Comet	T	AD	LD	FTC yrs.	FTP yrs.	C3 $(km/s)^2$	Mo kg.	ΔVPL1 km/s	ΔVPL2 km/s
Kopff	1996 Jul. 2	-890	1990 Jul. 4	3.6	6.0	81.1	2532	1.80	0.63
		-100	1991 Jul.13	4.7	5.0	76.0	2787	2.19	0.48
Wild 2	1997 May 7	-845	1991 Mar. 9	3.9	6.2	76.0	2787	1.99	0.60
		-341	1992 Mar.22	4.2	5.2	76.0	2787	2.40	0.19
Honda-Mrkos-Pajdusakova	1995 Dec.26	-100	1990 Nov.14	4.8	5.1	76.1	2767	2.64	-0.07
		- 50		5.0	5.1	76.0	2787	2.58	-0.01

Recently the comet Kopff 1996 opportunities were recommended for the proposed first rendezvous mission to a comet by NASA's Mariner Mark II spacecraft project. The recommended mission included a flyby of one or two main belt asteroids with a flyby of C-type asteroid 772 Tanete being an attractive opportunity enroute to the comet Kopff rendezvous (see Figure 1).

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

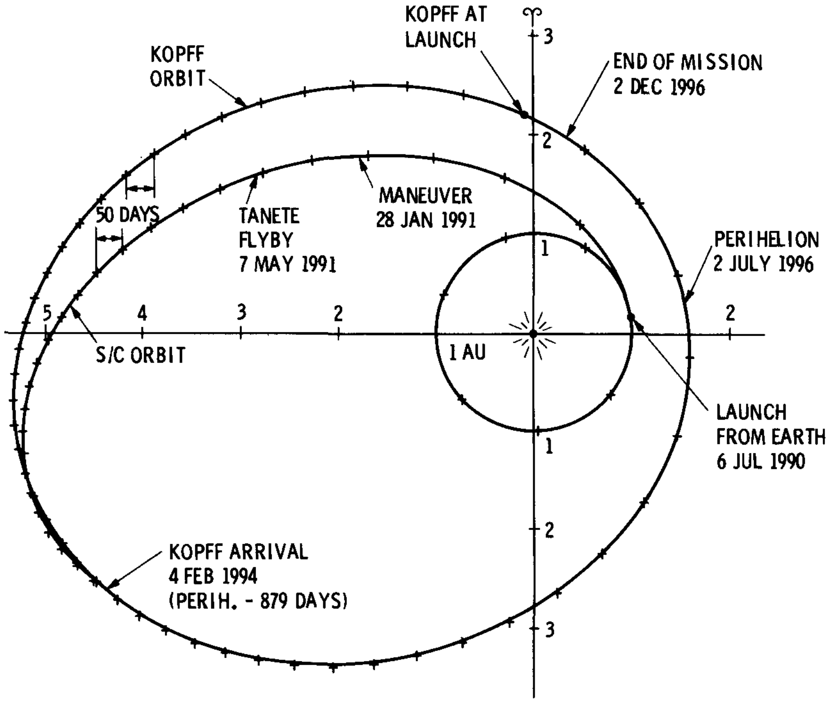

Figure 1. Orbit diagram of Kopff rendezvous with enroute flyby of Asteroid 772 Tanete.

References:

Marsden, B.G.: 1968, "Comets and Nongravitational Forces", Astronomical Journal, Vol. 73, No.5, Part 1, June 1968, pp.367-379.

Marsden, B.G.: 1982, "Catalogue of Cometary Orbits" Minor Planet Center, Central Bureau for Astronomical Telegrams.

NAS-ESF Joint Working Group on Planetary Exploration; Report of the Primitive Bodies Study Team, October, 1983.

Reinhard, R.: 1982, "Space Missions to Halley's Comet and Related Activities" ESA Bulletin, No.29, February 1982, pp.68-83.

Yen, C.L. : 1983, "Ballistic Comet Rendezvous Mission Opportunities", presentation to NASA's Comet Rendezvous Science Working Group, October 11, 1983.

Yen, C.L.: 1984, "Mariner Mark II Comet Rendezvous Mission Performance Update",presentationto NASA's Comet Rendezvous Science Working Group, Jan. 11, 1984.

Yeomans, D.K., Ananda, M., Sjogren, W.L., and Wood, L.J.: 1980, "Cometary Mass Determination" The Journal of the Astronautical Sciences, Vol. 29, No.1, Jan.-Mar. 1980, pp.19-33.

https://doi.org/10.1017/S0252921100084104 Published online by Cambridge University Press