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Missions to Comets: An Options Review

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National Aeronautics and
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Kenneth L. Atkins

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Foreword

It should be recognized at the outset that a great many ways may exist to view a list of cometary apparitions in order to determine an "optimum" mission opportunity. Optimum is a subjective word; it depends in large measure on how well the "payoff" meets a set of constraints or selection criteria. The various criteria that have been generally accepted and validated in numerous forums in recent years provide the starting point for this review. From that point, I have extended the selection process to identify those options that remain for consideration as the first comet rendezvous mission.

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Introduction

Have we examined all the possibilities? Is there a chance that the "perfect" mission is still there waiting for our discovery? What assurances have we that our selection of a prime mission is the right one, made after a thorough search? These are the questions that provide the genesis for this review, requested by the FY78 Cometary Science Working Group (CSWG).

There is a relatively extensive history of search activities for attractive comet mission opportunities. The activities were sketchy and not systematic until the Space Science Board (SSB) of the National Academy of Sciences heard strong arguments at a summer study in 1970[1] on the benefits of studying comets from spacecraft. The outgrowth was a recommendation to include a comet exploration program in NASA's overall thinking.

Approximately one year after the 1970 Woods Hole summer study, the Planetary Programs Office in NASA's Office of Space Science initiated several study projects concerning the small-body program. In 1971, an Ad Hoc Comet and Asteroid Mission Study Panel[2], composed of scientists, NASA Headquarters personnel, and personnel from NASA field centers, was formed. This panel included mission analysts to identify attractive mission opportunities for meeting the science objectives. In conjunction with the activity of the NASA panel, a symposium on comets[3] was held that included consideration of science strategy and several missions. In general, the mission selection process during this period emphasized opportunities from the mid-1970s to 1985[4-8]. Missions that emerged during these studies emphasized fast flybys, although capability to rendezvous through use of ion propulsion was recognized. The 1971 ad hoc panel was followed in 1973 by a more formally organized Committee on Comets and Asteroids. Again, the NASA committee of scientists was supported by NASA center and contractor personnel specializing in mission analysis. The search range for comet opportunities was broadened to examine options through the year 2000.

The key word in pursuing these searches was "opportunity." What actually constitutes an opportunity? Just because a comet has been sighted does not automatically mean that an opportunity exists to fly an instrumented spacecraft to it. A practical selection rationale was required based both on the technical and economic ability to deliver payload and on the potential science return. During this period, serious consideration was given to rendezvous and slow flybys that used ion propulsion. Opportunities at Comet Encke in 1980 and 1984 received the primary focus, but NASA funding restrictions precluded project starts for either of these opportunities.

Throughout these efforts to secure approval for a comet mission, there was a continuing need to separate practical mission options from the entire field of cometary apparitions through the year 2000. To accomplish this screening, it was necessary to develop quantifiable criteria relative to technical feasibility and science objectives and apply them to the lists of cometary appearance schedules.

The Criteria

The technical capability to deliver payload implies consideration of the orbital characteristics of the candidate comet and its timing with respect to Earth. At first glance, this could be taken to mean that it was necessary only to search for minimum-energy transfers to intercept the comet at some selected position in its orbit. If the objective were just "payload delivery," a search for minimum-energy transfers might suffice; however, the primary concern must be the return of an acceptable quantity of scientific data. This implies a bounded relation between the vehicle and the comet, and brings in considerations of the comet environment (model), relative motion, observation time, etc. It broadens the selection criteria beyond considering only a simple intercept, and forces inclusion of orbital characteristics such as inclination, eccentricity, Earth-comet distance, and arrival timing.

The earlier studies provided the bulk of rationale for determining selection criteria. The criteria were generally revalidated during each successive comet study. Table 1 provides a summary list showing the general categories of selection criteria and the specific parameters used to quantify them.

The selection rationale that derives from Table 1 concludes that cometary orbits with low orbital inclinations and low eccentricities require less propulsion energy to match their orbits; hence, a reduced technical capability is necessary to deliver a payload. Reduced technology requirements should imply lower overall project costs.

Opportunities with low Earth-comet distances during the time interval from about 100 days before perihelion to 100 days after are attractive

Table 1. Selection criteria

General Criteria	Specific Criteria (Quantifiable Parameters)
Technical capability for payload delivery	Inclination
Probability of meaningful data return	Eccentricity
Comet characteristics (scientific)	Earth-perihelion distance
	Nongravitational forces
	Sighting conditions
	Perihelion distance
	Number of observed apparitions
	Size
	Activity or model

because close proximity should tend to ensure adequate data return during the comet's more active period. Low Earth-comet distances during this period also often imply a reduced flight time, shorter system lifetime requirements, and consequently higher spacecraft reliability.

The correlation between data measured in situ and simultaneous Earth-based observations is also important. This implies that the comet should be visible from Earth during the encounter period. The Illinois Institute of Technology Research Institute (IITRI) defined a sighting criterion for target selection[5-8]. IITRI's recovery criterion ranked candidates according to the total number of hours they could be observed at a magnitude of 20 or better, prior to 100 days before their perihelion passage. The cumulative number used in the ranking required observability for two hours per day with the comet 25 deg above the local horizon and the Sun some 18 deg below the horizon. Also, to place in the category of good sighting, IITRI required magnitudes less than 12 at 100 days before perihelion. This tends to identify opportunities with low Earth-comet distances, "good" usually meaning that the minimum distance was less than 1.0 AU at some point in the near-perihelion zone of the comet's orbit.

To ensure maximum science benefit, and to permit instruments and their sensitivities to be selected as accurately as possible, an additional selection consideration should involve the number of recorded apparitions and the resulting accumulated knowledge about the comet's nature, its environment, and the activity that will be encountered by the approaching spacecraft. Any comet considered as a possible mission target should have fairly detailed observations on at least two apparitions. In addition, observations should be recent. Thus, comets with the shortest possible periods should, all other criteria notwithstanding, be good mission candidates.

A general measure of the comet's "size" is also included. If a comet exhibits a large coma, it should provide more observational time for a spacecraft in transit. Actually, it is extremely difficult to establish an accurate size, especially since coma size for a particular comet varies with solar distance; however, Bender[10] classified comets according to the maximum observed angular size of the coma at perihelion. A rating of "large" implies a subtended angle of 1 minute of arc or greater, with a total magnitude at perihelion of 6 or less. "Medium" includes coma sizes of 0.3 to 1.0 arc-minute and magnitudes generally in the 6 to 14 range.

Finally, it is important to know the comet's position as precisely as possible for navigation purposes. Thus, comets with large nongravitational forces leave a measure of uncomfortable uncertainty in their position, and this affects the feasibility of accurate navigation to the target.

The above discussion constitutes a brief review of the general and specific criteria historically used in the selection of the most promising opportunities. While some of these criteria may not apply strictly in a decision on a possible mission, they appear collectively to provide a logical rationale for determining the best available opportunities. If all or most of the criteria are met by a comet apparition, then that opportunity must certainly qualify as a strong candidate.

The Opportunities

There are 65 periodic comets that will return to perihelion in the time interval 1985 to 2010. The number of perihelion passes that the collective group will make between 1985 and 2010 is 197. The listings of the comets and their projected perihelion passages have been formally collected and tabulated by Bender[10] after an extensive literature search and data collection effort. The list of 197 passes thus covers the entire field of possible opportunities between 1985 and 2010. Bender considered each of the passes as a mission opportunity by partially applying the criteria shown in Table 1. This initially led to a separation of the passes into three categories of interest for mission opportunities:

1. Primary Interest: Those with large coma and absolute magnitude brighter than 12, and those with medium coma with a tail observed in recent years or absolute magnitude brighter than 10.5.
2. Secondary Interest: Those remaining with medium (or larger) coma and those with small coma but with an observed tail or absolute magnitude brighter than 13.
3. Low Interest: All other passes, including those comets not detected during their last five predicted returns.

Bender then added the criteria dealing with Earth correlation (sighting, perihelion distance, Earth-perihelion distance) and developed a list that contains all of the most important single-comet mission opportunities from the present through the year 2010. Table 2 lists the 36 opportunities in the time span from 1985 (the earliest programmatically possible launch date) until 2010, and presents information for use in further selection processes. All 36 opportunities accrue from favorable passes of only 20 of the original 65 comets in Bender's beginning list. The reason is that although the original 65 comets provided a ''potential'' list of 197 passes for consideration, even a partial application of the Table 1 criteria quickly reduces the number of practical, interesting mission opportunities to just 36. The 36 opportunities of Table 2 can be arranged chronologically to find those candidates providing the earliest possible rendezvous mission. Table 3 presents this ordering through 1993.

The Halley '86 option is no longer viable for a rendezvous mission because of programmatic and funding constraints. To perform the rendezvous, a launch in 1982 was required, with a ''new start'' for the project in FY79. Prior commitments of NASA funds to other programs such as the Space Telescope and Galileo precluded the required commitments for Halley rendezvous funding. However, the Halley '86 apparition remains a viable flyby mission candidate in conjunction with the first rendezvous mission. Trajectories have been developed that allow deployment of a probe at Halley from a passing ''mother'' ship en route to rendezvous at Tempel 2 '88 and Encke '90.

The next chronological option after Halley is the Encke '87 passage. This option's primary disadvantages are the relative Earth-comet geometry at the rendezvous arrival and the low perihelion (0.34 AU) that will make spacecraft thermal control more difficult. The Earth-relative geometry does improve within a short time after rendezvous as the comet swings through perihelion.

Table 2. Mission opportunities through the year 2010 (for launches in 1985 or later)

Comet	Perihelion Date	Peri. Distance, AU	Period, years	Eccentricity, deg	Inclination	Absolute Magnitude	Minimum Earth Distance/Time Rel. to Peri., AU/days	Observed Characteristics
1. Ashbrook-Jackson	1993 Jul 14	2.28	7.4	0.4	12.5	6.7	(1.39/83)	Large coma; strong nucleus; faint broad tail
2. Brorsen-Metcalf	1988 Nov 7	0.48	69	0.9	19.2	9.6	(0.38/-37)	Large coma; weak nucleus; long tail
3. Churyumov-Gerasimenko	1996 Jan 20	1.28	6.6	0.6	7.1	10.4	(0.4/-23)	Medium coma; strong nucleus; tail
	2009 Jan 16						(0.9/-100)	
4. Comas-Sola	2005 Mar 8	1.83	8.8	0.6	13.0	11.6	(1.07/-91)	Large coma; strong nucleus; fan shaped tail
5. D'Arrest	1995 Jul 7	1.3	6.4	0.62	19.6	11.5	(0.66/33)	Large, fan-shaped coma; weak nucleus; no tail
6. Encke	1987 Jul 17	0.34	3.3	0.85	11.9	9.7 pre-peri	(0.89/29)	Medium coma, fan-shaped toward sun; strong nucleus; narrow tail
	1990 Oct 28						(0.73/-32)	
	1994 Feb 9						(0.65/-2)	
	1997 May 23					12.2 post-peri	(0.42/38)	
	2000 Sep 28						(1.14/-22)	
	2004 Jan 17						(0.51/-24)	
	2007 May 7						(0.26/45)	

Table 2 (cont'd)

Comet	Perihelion Date	Peri. Distance, AU	Period, years	Eccen- tricity	Inclina- tion, deg	Absolute Magnitude	Minimum Earth Distance/Time Rel. to Peri., AU/days	Observed Characteristics
7. Faye	1991 Nov 15	1.59	7.3	0.58	9.1	10.8	(0.61/-15)	Large coma; strong nucleus; faint, diffuse tail
8. Giacobini-Zinner	1998 Nov 24	1.03	6.6	0.71	32.0	10.0	(0.66/6)	Large coma; strong nucleus; long tail
9. Halley	1986 Feb 9	0.59	76	0.97	162	5.0	(0.62/-74)	Very large coma; weak nucleus; very strong tail
10. Honda-Mrkos-Pajdusakova	1990 Sep 13 1995 Dec 30 2006 Sep 11	0.54	5.3	0.82	4.2	11.6	(0.29/-44) (0.10/42) (0.30/-42)	Medium coma; weak nucleus; tail
11. Kearns-Kwee	1990 Nov 24 1999 Sep 18 2009 Feb 23	2.34	9.0	0.49	9.0	8.6	(1.26/35) (1.56/100) (1.50/-100)	Very large, fan-shaped coma; trace of tail
12. Kopff	1996 Jul 2 2009 Jun 4	1.57	6.4	0.55	4.7	10.0	(0.57/-9) (0.70/54)	Very large coma; strong nucleus; narrow tail
13. Oterma	2002 Dec 30	5.47	19.4	0.24	1.9	9.6	(4.48/-34)	Medium coma; strong nucleus; narrow tail

Table 2 (cont'd)

Comet	Perihelion Date	Peri. Distance, AU	Period, years	Eccentricity	Inclination, deg	Absolute Magnitude	Minimum Earth Distance/Time Rel. to Peri., AU/days	Observed Characteristics
14. Schaumasse	1993 Mar 5	1.21	8.3	0.7	11.8	10.0	(0.59/-46)	Very large coma; weak nucleus; long tail
15. Schwassmann-Wachmann 1	1989 Aug 30	5.78	14.9	0.05	9.3	6.4	(4.79/22)	Very large coma; no tail; large outbursts
16. Schwassmann-Wachmann 2	1994 Jan 24	2.07	6.4	0.40	3.8	10.1	(1.09/8)	Medium coma; strong nucleus; broad tail
17. Shajn-Schaldach	1993 Nov 16 2000 Oct 13 2008 Jan 20	2.34	7.3	0.41	6.2	7.6	(1.63/100) (1.23/1.5) (1.57/-100)	Very large coma; weak nucleus; tail
18. Tempel 2	1988 Sep 17 1999 Sep 8	1.38	5.3	0.54	12.4	8.5	(0.77/-80) (0.64/-55)	Large, fan-shaped coma; weak nucleus; tail
19. Tuttle	2008 Jan 11	1.01	13.5	0.82	54.7	6.5	(0.08/-20)	Large coma; weak nucleus; no tail recently
20. Tuttle-Giacobini-Kresak	1990 Feb 8 2006 Jun 27	1.06	5.5	0.66	9.2	11.5	(1.09/-15) (1.42/-100)	Very large coma; strong nucleus; tail

Table 3. Chronological perihelion passages (mission options) through 1993

1. Halley 1986
2. Encke 1987
3. Brorsen-Metcalf 1988
4. Tempel 2 1988
5. Schwassmann-Wachmann 1 1989
6. Tuttle-Giacobini-Kresak 1990
7. Encke 1990
8. Honda-Mrkos-Pajdusakova 1990
9. Kearns-Kwee 1990
10. Faye 1991
11. Ashbrook-Jackson 1993
12. Schaumasse 1993
13. Shajn-Schaldach 1993

The Brorsen-Metcalf '88 opportunity does not appear to be a strong competitor for the first mission. Its orbital inclination of 19 deg and its eccentricity of 0.92 make the rendezvous relatively difficult in comparison with most of the other 20 comets. The implication is that a very high-performance system capability, approaching that of the Halley rendezvous, might be required. In addition, the orbit is deemed extremely erratic, and adequate navigation would be difficult to accomplish. Also, since B-M's period is 69 years, there will be no opportunity to observe it again prior to launch. It was last seen in 1919.

The Tempel 2 '88 apparition has been investigated fairly thoroughly. It is the least technically difficult of the early mission options. The trajectories developed to date for the Tempel 2 option also provide a good opportunity for the Halley-probe combination. The reduced technical requirements imply that this option will be the least costly of any in the list.

The next chronological opportunity is Schwassmann-Wachmann 1 '89. No serious mission interest has developed in the past for this opportunity, possibly because its perihelion is 5.78 AU.

There are four opportunities with 1990 perihelion passages: Tuttle-Giacobini-Kresak, Encke, Honda-Mrkos-Pajdusakova, and Kearns-Kwee. Of these, essentially all of the mission interest has centered on Encke. It seems likely that Encke's short period, and thus its large number of past observations, have kept it at the focus of mission interest over the other options in the '90 group. Encke's '90 passage offers a very good geometrical relation with Earth, in contrast to its '87 passage, but high orbital eccentricity and the difficult thermal environment associated with the 0.34-AU perihelion require a higher-performing system than that for the Tempel 2 '88 opportunity. This, in turn, implies higher project cost. Perhaps, the 2.34-AU perihelion distance argues strongly against Kearns-Kwee as the preferred 1990 candidate.

Both T-G-K and H-M-P have lower perihelion than Kearns-Kwee and thus may exhibit more of the preferred activity for good science return. T-G-K and H-M-P also provide "good" Earth-relative geometries at their 1990 apparitions, enhancing Earth-based data correlation potential. Both targets require trajectories of about 975 days, although the launch to H-M-P comes almost 7 months later than the T-G-K mission (November 1987 for H-M-P and April 1987 for T-G-K). The H-M-P mission is energetically more difficult and requires a higher-performing system. The implication is again for higher project costs. H-M-P is not as demanding as the Encke '90 option, however.

In ascending order of difficulty, the '90 options are: (1) T-G-K, (2) H-M-P, and (3) Encke. In launch date chronology, th[illegible] are: (1) T-G-K, 4/'87; (2) H-M-P, 11/'87; and (3) Encke, 3/'88.

All of the 1991 to 1993 grouping seem at first to present fairly good opportunities. Faye '91 and Schaumasse '93 offer the closest Earth approach distances of the four in the group, while Ashbrook-Jackson '93 offers the lowest absolute magnitude. However, Brian Marsden[3] has recommended that Schaumasse be avoided because of its erratic nongravitational force behavior. A mission to Faye '91 would not require launch until the end of 1988 for a three-year flight time. Faye '91 is not a viable option for inclusion of a Halley probe because it would add another year beyond combinations based on the 1990 targets (e.g., Halley/Encke '90).

No quantitative mission data worth mentioning are available relative to Ashbrook-Jackson and Shajn-Schaldach. Probably because the perihelion distances for these comets are 2.28 and 2.23 AU, respectively, little or no scientific interest has been displayed in either as a target.

If perihelion greater than 2.0 AU and erratic behavior are used as additional screening criteria, then not only do Schaumasse, Ashbrook-Jackson, and Shajn-Schaldach opportunities disappear from Table 3, but Schwassmann-Wachmann 1 '89, and Kearns-Kwee '90 drop out also. Then, since Halley '86 is no longer a viable rendezvous candidate, and if Encke '87 is unacceptable because of an Earth-based sighting criterion, the list in Table 3 is rapidly reduced to only five opportunities (4, 6, 7, 8, 10). These five are listed in Table 4.

Table 4. Options through 1993 remaining after application of selected criteria

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1. Tempel 2 '88*
2. Tuttle-Giacobini-Kresak '90
3. Encke '90*
4. Honda-Mrkos-Pajdusakova '90
5. Faye '91

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*Halley probe deployment options identified.

Of the five, Tempel 2 '88 and Encke '90 are the only ones that provide a reasonable option for probe deployment at Halley. Encke '90 with Halley-probe already projects more than four years of flight and will demand significant technology advances in performance and ion-engine lifetime.

Summary

This review has examined the available options for a first rendezvous mission to a comet. The starting point was provided by a number of past "opportunities surveys" that were updated and coalesced by Bender in 1974. The most promising opportunities developed by Bender were examined against several additional criteria, both programmatic and technical. Bender's original lists show that initially there are only 36 perihelia of interest between 1985 and 2010. The examination of the chronological listing through 1993 under the added criteria reduces the number of options to those in Table 4. The earliest of these remaining options is Tempel 2 '88.

References

1. Space Science Board, *Priorities for Space Research 1971–1980*, National Academy of Sciences, Washington, D.C., 1971.
2. Stuhlinger, E., et al., *Comets and Asteroids: A Strategy for Exploration*, Report of the Comet and Asteroid Mission Study Panel, NASA TM X-64677, May 1972.
3. Roberts, D. L., *Proceedings of the Cometary Science Working Group*, IIT Research Institute Publication, 1971.
4. Roberts, D. L., Narin, F., and Pierce, D. M., *A Survey of Comet Missions*, Report M-7, IIT Research Institute, May 1965.
5. Roberts, D. L., Narin, F., and Pierce, D. M., *Cometary Study by Means of Space Missions*, Report M-8, IIT Research Institute, August 1965.
6. Narin, F., Roberts, D. L., and Pierce, D. M., *Missions to the Comets*, Report M-9, IIT Research Institute, December 1965.
7. Narin, F., and Pierce, P. M., *Perturbation, Sighting and Trajectory Analysis for Periodic Comets: 1965–1975*, Report T-7, IIT Research Institute, October 1964, corrected September 1966.
8. Narin, F., and Rejzer, B., *Sighting and Trajectory Analysis for Periodic Comets: 1975–1986*, Report T-11, IIT Research Institute, March 1965.
9. Whipple, F., et al., *The 1973 Report and Recommendations of the NASA Science Advisory Committee on Comets and Asteroids*, NASA TMX-71917, 1973.
10. Bender, D. F., *A Survey of Possible Missions to the Periodic Comets in the Interval 1974–2010*, JPL Technical Memorandum 33-684, April 1974.

NASA–JPL–Coml., L.A., Calif.