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LOW LAUNCH-ENERGY TRAJECTORIES TO THE OUTER SOLAR SYSTEM VIA VENUS AND EARTH GRAVITY-ASSIST FLYBYS

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Recent cancellation of the program to develop a Centaur upper stage for use in the Space Transportation System (STS) has motivated considerable interest in trajectory modes with low launch-energy requirements to the outer solar system. Flyby encounters of the inner planets, especially Venus and Earth, may be used to enable missions to Jupiter, Saturn, and a restricted class of comets. An examination of mission opportunities to these targets is presented through the end of this century using gravity-assist trajectories.

International

INTRODUCTION

Direct trajectories, ballistic transfers with no intermediate flyby encounters, have historically been preferred in trajectory design for missions to the outer solar system. They allow the shortest flight time to a particular target body, reducing the science return delay and operations costs. Navigation complexity is reduced and spacecraft design simplified as compared to missions which travel significantly inside Earth's orbit. However, as payload requirements increase, or in the absence of available launch vehicles with sufficient performance, it may be necessary to use indirect trajectories to achieve viable missions to the outer solar system.

It has been well known for many years that gravity-assist flybys of planets, including Earth, can be used to reduce launch energy. As early as the 1960s, previous investigators[1,2,3,4,5] proposed using Jupiter swingbys to increase the heliocentric energy of the spacecraft transfer orbit and enable missions to the outer planets. This principle was implemented successfully in the two Voyager missions, where a flyby of each giant planet was successively used to target the spacecraft to their next planetary encounter. Several years earlier, the Mariner Venus-Mercury mission, launched in November 1973, used Venus to lower the spacecraft's perihelion and set up a series of Mercury encounters.

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The classical ΔV-EGA (ΔV-Earth-Gravity-Assist) and VEGA (Venus-Earth-Gravity-Assist) trajectory concepts were introduced by Hollenbeck[6] in 1975 for trajectories to Jupiter and Saturn. Bender and Friedlander[7] examined multi-asteroid flyby opportunities enabled by these inner-planet flyby techniques. A systematic classification of VEGA and ΔV-EGA trajectories to Jupiter, Saturn, and Uranus for launch opportunities in the 1980s was performed by Stancati, Friedlander, and Bender.[8] Diehl[9] demonstrated that a second Earth flyby could be used to eliminate or substantially reduce the ΔV requirements inherent with a VEGA trajectory to Jupiter. The resulting new transfer mode is called a VEEGA (Venus-Earth-Earth-Gravity-Assist) trajectory. The application of VEEGA trajectory design to the Galileo mission is treated by D'Amario.[10]

The purpose of this study is to define potential inner planet gravity-assist trajectory modes for missions to Jupiter, Saturn, and selected comets of high scientific interest. The investigation is restricted to launch opportunities from 1992 to 2001. A discussion of the trajectory concepts for VEGA and VEEGA trajectories to outer solar system targets is given in the next section. Subsequent sections identify trajectories to the targets of interest.

TRAJECTORY DESIGN CONCEPTS

Gravity-assist trajectories, as a class, utilize the fact that the inner planets, especially Earth and Venus, have a substantial capability for modifying the spacecraft's heliocentric orbit characteristics. In a VEGA or VEEGA trajectory, the launch vehicle is used to inject the spacecraft on a transfer with a perihelion inside Venus' orbit, reducing the heliocentric energy of the spacecraft. In the event that the correct timing, or phasing, of the encounter sequence can be arranged, this investment of heliocentric energy results in a large change in orbit geometry and orientation after the Venus flyby. To capitalize on the Venus flyby, trajectories to the outer solar system require that the encounter occur along a nontangential approach to the orbit of Venus. The flight-path angle is necessary so that the gravity assist from Venus, which targets the spacecraft to its next planetary encounter, results in a gain in the spacecraft's heliocentric energy.

Trajectories examined in this study all begin with an initial planetary flyby of Venus for which the launch energy requirements are significantly below those typical of ΔV-EGA transfers. Typical launch C_3 (hyperbolic excess velocity squared), or V_∞^2, requirements for two-year ΔV-EGAs are between 26 and 30 km^2/s^2. VEEGA trajectories to Jupiter, Saturn, and selected comet targets can have launch C_3 requirements as low as 10 km^2/s^2.

For VEGA and VEEGA trajectories, the Venus-Earth transfer establishes the spacecraft's relative velocity at Earth. A high V_∞ magnitude at the final Earth encounter is required for outer solar system targets: greater than 9 km/s for trajectories to Jupiter and 10 km/s for trajectories to Saturn. The Venus-Earth transfer also defines the incoming V_∞ direction at Earth. Either one Earth flyby (VEGA trajectories) or two Earth flybys (VEEGA trajectories) are used to achieve the required outgoing V_∞ direction to the outer solar system.

A characteristic of VEGA trajectories is that a single Earth flyby may not be sufficient to rotate the incoming relative velocity vector to its required outgoing direction. Consequently, a maneuver after the Earth flyby may be used to complete the proper orientation of the velocity. VEGA trajectories which do not require a maneuver after the Earth flyby are characterized by highly energetic Venus-Earth transfers and require relatively large flight-path angles at Venus; this can more easily be achieved with Type III or Type IV Earth-Venus transfers. Heliocentric transfers between celestial bodies may be classified according to the transfer angle between the two bodies. The classification is as follows: Type I (0° to 180°), Type II (180° to 360°), Type III (360° to 540°) and Type IV (540° to 720°).

The two Earth flybys of a VEEGA trajectory can eliminate or substantially reduce the ΔV requirements which may be present in a VEGA transfer since the relative velocity rotation can be split between the two Earth encounters. In the resonant case, the time interval is an integral number of years; in this study, the interval is restricted to two or three years. If the trajectory plane coincides with the Earth orbital plane, it is possible to have nonresonant transfers where the time interval between Earth encounters may be several months greater or less than the time interval for resonant transfers.

The Venus and Earth encounters must be designed so that the final Earth flyby is phased properly for a transfer to the target body, ensuring that the target body is at the rendezvous position when the spacecraft crosses the target's orbit. Errors in the phasing of the encounter sequence are tightly coupled to penalties in launch-energy and postlaunch ΔV requirements. VEEGA trajectories provide more flexibility than VEGA trajectories in establishing the proper phasing of the flyby sequence. Additional benefits are realized when resonant transfers between the VEEGA Earth flybys can provide some of the inclination change required for transfers to comets.

Illustrations of VEGA and VEEGA trajectories to the same target body, in this case Jupiter, are provided in Figure 1. For these two trajectories as well as the other trajectories in this paper, the Venus and Earth flybys are designed to satisfy energy, orientation, and phasing requirements at the final Earth flyby for a direct transfer to the target body.

LOW LAUNCH-ENERGY TRAJECTORIES TO JUPITER

A summary of VEGA and VEEGA trajectories to Jupiter that were identified in this study is presented in Table 1. Trajectories are grouped according to launch opportunities to Venus. Opportunities to Venus for similar-type (I,II,III, or IV) Earth-Venus transfers occur about every 19 months due to the Earth-Venus synodic period.

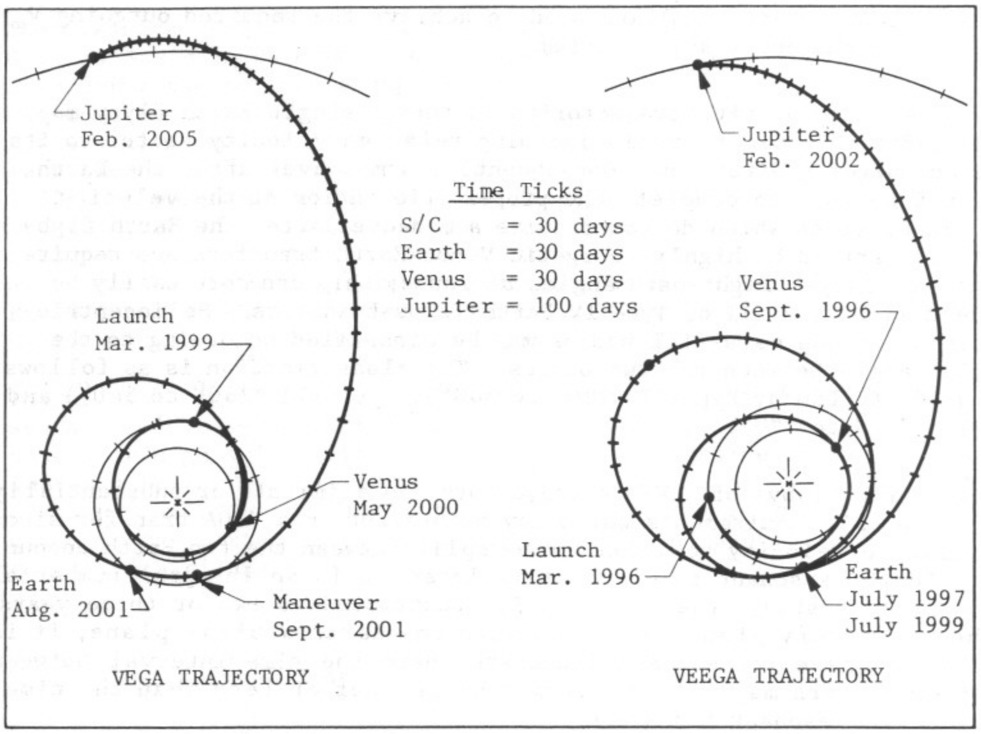


Fig. 1 Sample VEGA and VEEGA Trajectories

Table 1

TRAJECTORIES TO JUPITER

	Launch Date	Trajectory	C_3 (km^2/s^2)	Deep Space ΔV (m/s)	Orbit Insertion ΔV (m/s)	Arrival Date	Flight Time (yrs)
1.	Aug 92	VEGA	11	397	870	Jan 98	5.4
2.	Oct 92	VEEGA	13	95	867	Dec 99	7.2
3.	Jan 93	VEEGA	10	137	825	Dec 98	5.9
4.	Mar 94	VEEGA	12	0	795	Oct 00	6.6
5.	Oct 94	VEEGA	19	0	808	Sept 00	5.9
6.	Dec 95	VEGA	17	373	822	Nov 00	4.9
7.	Jan 96	VEEGA	16	0	751	Jan 03	7.0
8.	Feb 96	VEEGA	19	0	774	July 02	6.4
9.	Mar 96	VEEGA	11	0	723	Feb 02	5.9
10.	May 97	VEEGA	12	110	829	May 05	7.9
11.	Oct 97	VEGA	20	810	840	Nov 02	5.0
12.	Nov 97	VEEGA	17	62	739	Oct 04	6.9
13.	Mar 99	VEGA	12	666	820	Feb 05	6.0
14.	Mar 99	VEEGA	12	0	744	July 06	7.4
15.	Mar 99	VEGA	19	557	953	Oct 03	4.6
16.	June 99	VEEGA	12	0	747	Feb 06	6.7
17.	Aug 00	VEEGA	9	0	851	Apr 07	6.7
18.	Jan 01	VEGA	22	747	892	Mar 06	5.1
19.	Feb 01	VEEGA	14	0	767	Oct 07	6.6

The VEGA trajectories, as compared to VEEGA trajectories, are characterized by shorter flight times and larger deep-space ΔV requirements. Other VEGA and VEEGA trajectories to Jupiter exist for these launch years, but have either larger launch C_3, larger ΔV or longer flight-time requirements.

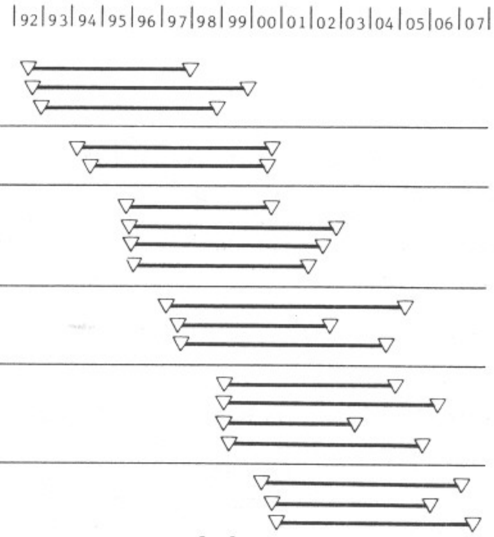
Each trajectory shown in Table 1 is a member of a family of trajectories. Variations of each trajectory exist with different combinations of launch C_3, ΔV and flight time to Jupiter. It was assumed that these trajectories were to be utilized for orbiter missions; therefore, the flight time is biased to reduce orbit insertion ΔV requirements. Flight times could be reduced, however, at the expense of additional deep-space or orbit-insertion ΔV. There was no requirement that the trajectories be ballistic to Jupiter. Consequently, deep-space ΔV was allowed if it could provide a significant reduction in launch-energy requirements. A 200-day orbit period and 4-Rj (Jupiter radii) orbit periapsis were assumed for orbit-insertion ΔV calculations.

Launch date and arrival date information for these trajectories is presented in a timeline format in Table 2. A summary of the transfer types between planetary flybys is given in Table 3. The Earth-Venus transfer is either a Type III or Type IV transfer for each of the VEGA trajectories. VEGA trajectories with Type I or Type II Earth-Venus transfers exist, but have larger ΔV requirements.

Table 2

TIMELINE FOR TRAJECTORIES TO JUPITER

Trajectory	C_3	ΔV
1. VEGA	11	1.3
2. VEEGA	13	1.0
3. VEEGA	10	1.0
4. VEEGA	12	0.8
5. VEEGA	19	0.8
6. VEGA	17	1.2
7. VEEGA	16	0.8
8. VEEGA	19	0.8
9. VEEGA	11	0.7
10. VEEGA	12	0.9
11. VEGA	20	1.7
12. VEEGA	17	0.8
13. VEGA	12	1.5
14. VEEGA	12	0.7
15. VEGA	19	1.5
16. VEEGA	12	0.7
17. VEEGA	9	0.9
18. VEGA	22	1.6
19. VEEGA	14	0.8



C_3 = launch energy in km^2/s^2

ΔV = total postlaunch ΔV in km/s

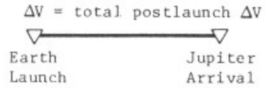


Table 3

TRANSFER GEOMETRY FOR TRAJECTORIES TO JUPITER

Launch Date	Trajectory	Earth-Venus Transfer (Type)	Venus-Earth Transfer (Type)	Earth-Earth Transfer	Earth-Jupiter Transfer (Type)
1. Aug 92	VEGA	III	III	---	I
2. Oct 92	VEEGA	IV	II	2-yr resonant	II
3. Jan 93	VEEGA	I	II	2-yr resonant	II
4. Mar 94	VEEGA	III	II	2-yr resonant	II
5. Oct 94	VEEGA	II	II	Type III	I
6. Dec 95	VEGA	III	III	---	I
7. Jan 96	VEEGA	IV	II	2-yr resonant	II
8. Feb 96	VEEGA	I	II	Type III	I
9. Mar 96	VEEGA	II	II	2-yr resonant	II
10. May 97	VEEGA	III	II	Type III	I
11. Oct 97	VEGA	IV	III	---	I
12. Nov 97	VEEGA	II	III	2-yr resonant	I
13. Mar 99	VEGA	IV	II	---	II
14. Mar 99	VEEGA	IV	II	Type III	I
15. Mar 99	VEGA	III	III	---	I
16. June 99	VEEGA	II	II	2-yr resonant	II
17. Aug 00	VEEGA	III	II	Type III	I
18. Jan 01	VEGA	IV	III	---	I
19. Feb 01	VEEGA	II	III	2-yr resonant	I

Many combinations of transfers exist for the VEEGA trajectories. Typically, VEEGA trajectories with Type I or Type IV Earth-Venus transfers alternate with Type II or Type III transfers with each 19-month Venus cycle. This is a consequence of the phasing requirements between the Earth, Venus, and Jupiter.

LOW LAUNCH-ENERGY TRAJECTORIES TO SATURN

A summary of the gravity-assist trajectories to Saturn is given in Table 4. Trajectories are grouped according to launch opportunities to Venus. The C_3 range for these trajectories is similar to those to Jupiter since Venus is still the initial planetary flyby. However, for the trajectory to eventually reach Saturn, it is necessary for the Venus-Earth transfer to establish a higher V_∞ magnitude at Earth than for the trajectories to Jupiter. All of the ballistic VEEGA trajectories to Saturn have exact or near three-year orbit periods between the Earth flybys. VEEGA trajectories with two-year orbit periods between the Earth flybys require a large maneuver after the second Earth flyby.

Table 4

TRAJECTORIES TO SATURN

	Launch Date	Trajectory	C_3 (km^2/s^2)	Deep Space ΔV(m/s)	Orbit Insertion ΔV (m/s)	Arrival Date	Flight Time (yrs)
1.	Sept 92	VEEGA	14	497	998	Jan 02	9.3
2.	Nov 92	VEEGA	16	0	983	Feb 03	10.3
3.	July 94	VEJGA	18	266	851	Sept 02	8.2
4.	Sept 94	VEEGA	11	551	888	Apr 04	9.6
5.	Sept 94	VEEGA	11	0	881	Dec 04	10.2
6.	Oct 94	VEEJGA	17	0	706	May 03	8.5
7.	Dec 95	VEJGA	16	591	425	Dec 04	9.0
8.	Dec 95	VEEGA	16	163	876	Dec 06	11.0
9.	Jan 96	VEEGA	16	370	903	July 05	9.5
10.	July 97	VEEGA	16	0	843	Mar 08	10.7
11.	Dec 97	VEEGA	17	0	879	Aug 07	9.7
12.	Jan 98	VEEGA	19	464	929	May 06	8.3
13.	Jan 99	VEEGA	20	0	909	June 09	10.4
14.	Mar 99	VEEGA	12	455	841	Jan 09	9.9
15.	Mar 99	VEEGA	18	0	1075	Dec 08	9.7
16.	Apr 99	VEEGA	14	0	834	Jan 10	10.8
17.	Aug 00	VEEGA	10	301	813	May 11	10.7
18.	Jan 01	VEEGA	14	180	823	Apr 12	11.2

In the late 1990s, the phasing between Earth, Jupiter, and Saturn allows for Jupiter gravity-assist flybys enroute to Saturn. VEJGA (Venus-Earth-Jupiter-Gravity-Assist) and VEEJGA (Venus-Earth-Earth-Jupiter-Gravity-Assist) trajectories can provide better performance and reduced flight times to Saturn as compared to VEGA and VEEGA trajectories. VEEJGA trajectories allow ballistic options with two-year Earth-Earth transfers. VEJGA trajectories to Saturn allow shorter flight times due to the absence of a second Earth flyby. These trajectories require deep-space maneuvers as have been observed for VEGA trajectories to Jupiter.

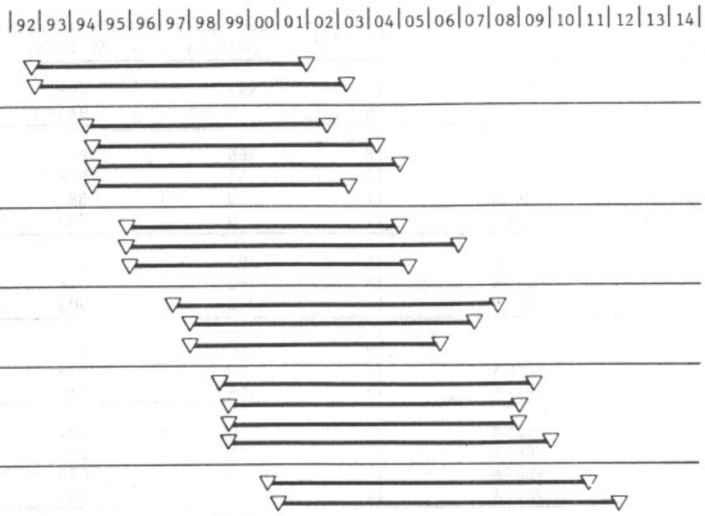
Flight times for these trajectories were also biased to reduce orbit-insertion ΔV requirements. Orbit-insertion ΔV calculations were made assuming a 96-day orbit period and a 2.2-Rs (Saturn radii) orbit periapsis. Shorter flight times to Saturn would require larger deep-space maneuvers and/or larger orbit-insertion maneuvers.

Launch date and arrival date information for these trajectories is given in Table 5 in a timeline format. A summary of the transfer types between planetary flybys is given in Table 6. For VEEGA trajectories to Saturn, Type II and Type IV launch opportunities to Venus alternate with each 19 month Venus cycle. The launch and arrival date space for Earth-Venus transfers is greater for Type II or Type IV transfers than for Type I or Type III transfers. This gives needed flexibility in finding a sequence of planetary flybys to satisfy the energy and phasing requirements for transfers to Saturn.

Table 5

TIMELINE FOR TRAJECTORIES TO SATURN

Trajectory	C_3	ΔV
1. VEEGA	14	1.5
2. VEEGA	16	1.0
3. VEJGA	18	1.1
4. VEEGA	11	1.4
5. VEEGA	11	0.9
6. VEEJGA	17	0.7
7. VEJGA	16	1.0
8. VEEGA	16	1.0
9. VEEGA	16	1.3
10. VEEGA	16	0.8
11. VEEGA	17	0.9
12. VEEGA	19	1.4
13. VEEGA	20	0.9
14. VEEGA	12	1.3
15. VEEGA	18	1.1
16. VEEGA	14	0.8
17. VEEGA	10	1.1
18. VEEGA	14	1.0



C_3 = launch energy in km^2/s^2

ΔV = total postlaunch ΔV in km/s

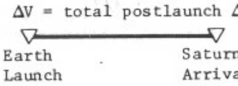


Table 6

TRANSFER GEOMETRY FOR TRAJECTORIES TO SATURN

Launch Date	Trajectory	Earth-Venus Transfer (Type)	Venus-Earth Transfer (Type)	Earth-Earth Transfer	Earth-Jupiter Transfer (Type)	Earth-Saturn Transfer (Type)
1. Sept 92	VEEGA	IV	II	Type III	---	I
2. Nov 92	VEEGA	IV	II	Type III	---	I
3. July 94	VEJGA	IV	III	---	I	---
4. Sept 94	VEEGA	II	III	2-yr resonant	---	I
5. Sept 94	VEEGA	II	III	3-yr resonant	---	I
6. Oct 94	VEEJGA	II	II	Type III	I	---
7. Dec 95	VEJGA	III	III	---	I	---
8. Dec 95	VEEGA	IV	II	Type III	---	I
9. Jan 96	VEEGA	IV	II	2-yr resonant	---	II
10. July 97	VEEGA	III	II	3-yr resonant	---	II
11. Dec 97	VEEGA	II	III	Type II	---	II
12. Jan 98	VEEGA	II	II	Type III	---	I
13. Jan 99	VEEGA	IV	II	Type III	---	I
14. Mar 99	VEEGA	IV	II	2-yr resonant	---	II
15. Mar 99	VEEGA	III	III	3-yr resonant	---	I
16. Apr 99	VEEGA	IV	II	3-yr resonant	---	II
17. Aug 00	VEEGA	III	II	3-yr resonant	---	II
18. Jan 01	VEEGA	II	III	Type II	---	II

LOW LAUNCH-ENERGY TRAJECTORIES TO COMET TARGETS

Table 7 presents the list of comets examined for VEGA and VEEGA trajectory opportunities. The selections were based on previous work[11] which outlined selection criteria to define scientifically interesting bodies for mission feasibility studies. Characteristically, the orbital motion of these comets has been well understood. They exhibit the processes desirable for study and have good viewing properties.

The primary purpose of the Comet Rendezvous Asteroid Flyby (CRAF) mission, with a planned launch in February 1993, will be to rendezvous with the short-period Comet Tempel 2 in late 1996. The CRAF objective, Tempel 2, as well as both backup targets, Wild 2 and Kopff, are included in the list of comets for this study.

Mission design studies for these comets have been included in previous reports. Yen[12] published a comprehensive catalog of transfer opportunities with launches after 1990 to a large set of comets using direct, VEGA, and ΔV-EGA modes. Stetson[13] and Miller[14] updated this list as it applies to the CRAF mission. The aim of the present study is to expand the known set of transfers to include the VEEGA trajectory class and thus provide a large set of high-performance mission opportunities available in the 1990s.

Table 7

COMET TARGETS CONSIDERED IN TRAJECTORY STUDY

Comet	Magnitude*	Apparitions	Perihelion Dates Considered
Tempel 2	9.7	20	Sept 99
		21	Feb 05
		22	July 10
Kopff	8.2	15	Dec 02
		16	May 09
Wild 2	9.4	5	Sept 03
		6	Feb 10
D'Arrest	9.3	17	Feb 02
		18	Aug 08
Encke	7.1	56	Sept 00
		57	Dec 03
		58	Apr 07
Giacobini-Zinner	9.6	14	July 05
Borrelly	8.6	14	July 08

*Approximate apparent magnitude at perihelion reduced to 1 AU from Earth

While the comet's physical properties may be used to determine whether the comet is scientifically interesting, the orbital properties ultimately determine whether a viable mission exists. Table 8 presents some relevant data concerning the orbits of the targets used in this study. These bodies are all classified as short-period comets, a restricted set with orbit periods of less than 100 years.

VEGA and VEEGA opportunities to a particular comet target occur infrequently compared to those for Jupiter and Saturn, as shown in Table 9.

For each cometary perihelion, there is an optimal date to fly by Earth that provides the best performance for a rendezvous mission. To link up with this optimal Earth departure for a given launch year, either two-year or three-year VEEGA trajectories, or VEGA trajectories can be used. Thus, launch opportunities tend to be grouped together spanning a period of two to three years, all with arrival dates before a particular comet perihelion, followed by a conspicuous period without viable launch opportunities. Another group of low launch-energy trajectories then appears with arrivals near the next comet aphelion. Table 10 reflects this organization, where launches to a comet with arrival near a particular aphelion are grouped together. For instance, launch opportunities to Kopff between late 1993 and early 1996 have arrivals in early 2000, shortly after Kopff aphelion. Kopff launch opportunities do not reappear until late 1997 for arrivals near the next aphelion in 2006.

While a particular comet may be available for a rendezvous mission only infrequently, mission opportunities with low-energy launch requirements

Table 8

COMET ORBIT CHARACTERISTICS

Comet	Period (years)	Ecliptic Inclination (deg)	Eccentricity	Aphelion (AU)	Perihelion (AU)
Tempel 2	5.5	12	0.52	4.7	1.5
Kopff	6.5	5	0.54	5.4	1.6
Wild 2	6.2	3	0.54	5.3	1.6
D'Arrest	6.5	20	0.61	5.6	1.4
Encke	3.3	12	0.85	4.1	0.4
Giacobini-Zinner	6.6	32	0.71	6.0	1.0
Borrelly	6.9	32	0.63	5.9	1.4

Table 9

TRAJECTORIES TO COMETS

	Comet	Launch Date	Trajectory	C_3 (km^2/s^2)	Deep Space ΔV (m/s)	Rendezvous ΔV (m/s)	Arrival Date	Flight Time (yrs)	Days to Perihelion
1.	Tempel 2	Feb 93	VEGA	13.9	1705	1906	Nov 96	3.8	1037
2.	Encke	Aug 94	VEGA	20.0	0	3141	Dec 98	4.3	634
3.	D'Arrest	Mar 93	VEEGA	18.5	494	2135	Feb 00	6.9	726
4.	Kopff	Nov 92	VEEGA	15.7	13	2269	Sept 00	7.8	817
5.		Feb 93	VEEGA	15.1	0	1931	Jan 01	8.0	684
6.		Feb 93	VEEGA	13.1	0	2370	Apr 00	7.2	960
7.		Apr 94	VEGA	14.2	1422	2649	Apr 00	6.0	963
8.		Sept 94	VEGA	11.0	2268	1131	Feb 00	5.5	1021
9.		Jan 96	VEGA	15.6	0	2913	Oct 01	5.7	416
10.	Wild 2	Sept 92	VEEGA	10.8	169	1928	Jun 01	8.7	827
11.		May 94	VEGA	15.2	2191	977	Mar 01	6.8	927
12.		Sept 94	VEEGA	11.3	161	2510	Dec 00	6.3	1002
13.		Oct 94	VEEGA	19.1	0	1905	May 01	6.6	847
14.	Encke	Dec 95	VEEGA	20.1	317	3414	July 02	6.6	520
15.		Aug 97	VEGA	13.0	201	3487	July 02	4.9	537
16.	Tempel 2	Feb 96	VEEGA	23.1	0	2771	Aug 02	6.5	921
17.		Feb 96	VEEGA	15.9	0	1792	Sept 03	7.6	528
18.		Mar 96	VEEGA	9.5	0	2974	Nov 01	5.7	1180
19.	Giaco-	Mar 94	VEEGA	15.2	29	3036	Jun 03	9.3	734
20.	bini-	Aug 94	VEEGA	12.6	447	3387	Nov 02	8.2	960
21.	Zinner	Aug 95	VEEGA	11.5	1269	2721	Apr 03	7.7	800
22.		May 96	VEEGA	16.6	0	3779	Feb 03	6.7	879
23.	Encke	Sept 99	VEEGA	23.9	259	3869	Dec 05	6.3	479
24.		Sept 00	VEGA	15.3	680	3644	Jan 06	5.3	461
25.	Borrelly	Jun 97	VEEGA	14.1	91	2877	Mar 06	8.8	844
26.		July 99	VEEGA	17.1	398	3620	Feb 06	6.5	900
27.	D'Arrest	Jun 97	VEEGA	14.5	0	2273	Nov 05	8.5	994
28.		Nov 97	VEEGA	17.5	0	2080	Apr 06	8.5	841
29.		Jun 99	VEEGA	23.3	790	2076	Dec 05	6.5	962
30.	Kopff	May 97	VEEGA	12.1	0	1694	Nov 06	9.5	906
31.		Sept 97	VEEGA	15.7	592	1852	Sept 06	9.0	974
32.		Mar 99	VEEGA	15.6	0	1771	July 06	7.4	1043
33.		May 99	VEEGA	12.1	557	1646	Feb 07	7.7	841
34.		Dec 00	VEGA	20.0	713	2001	Oct 06	5.8	953
35.		Mar 01	VEEGA	14.2	0	2345	Jan 08	6.7	492
36.	Wild 2	Jan 99	VEEGA	10.6	11	1691	Feb 07	8.1	1103
37.		July 99	VEEGA	14.1	0	1714	Dec 06	7.5	1149
38.		Sept 99	VEEGA	25.2	0	1928	Jan 07	7.3	1104
39.		Sept 00	VEEGA	13.5	0	2439	Aug 08	7.9	550
40.	Tempel 2	Dec 00	VEEGA	18.3	0	2906	Oct 07	6.7	983
41.		Jan 01	VEEGA	13.8	144	3134	Sept 07	6.7	1021
42.		Jan 01	VEEGA	21.5	58	1864	Apr 08	7.3	800
43.		Feb 01	VEEGA	13.8	105	3150	Aug 07	6.5	1063
44.		Mar 01	VEEGA	16.9	113	1381	Apr 08	7.1	804

to scientifically interesting comets occur throughout the remainder of the century. Table 10 presents a timeline of rendezvous opportunities organized in the same fashion as Table 9. One clear feature is the wide variation of flight time exhibited by trajectories in this mission set, from 3.8 years to 9.5 years. Table 11 shows the transfer modes used for each transfer leg of the trajectories described in Table 9. As an example, the May 1997 VEEGA to Kopff uses a Type III transfer from Earth to Venus (1.1 years), a Type IV transfer for the Venus return to Earth (2.0 years), a three-year resonant transfer back to Earth, and concludes with a Type II transfer from Earth to Kopff (3.4 years). This trajectory requires a launch C_3 of only 12.1 km^2/s^2 and consumes just 1694 m/s of postlaunch ΔV, but requires the longest transfer time, 9.5 years, of any trajectory studied.

Another trajectory class using a Venus flyby as the final departure encounter before comet arrival may have application to some cometary missions. VVGA (Venus-Venus-Gravity-Assist) trajectories to comets with perihelia near the orbit of Venus allow the possibility of lower rendezvous ΔVs than VEGA and VEEGA trajectories to the same comets. This concept was first discussed by Hollenbeck.[6] Bender[14] has identified VVGA launch opportunities in 1994 for several comets. VVGA trajectories to the outer solar system typically have higher launch-energy requirements than VEEGA trajectories, in order to establish the higher V_∞ magnitude at Venus required for a departure to the outer solar system. For the comets of interest in this study, no VVGA trajectories with acceptable performance were identified.

CONCLUSIONS

Venus-Earth gravity-assist trajectories to the outer solar system have some desirable performance characteristics for planetary missions. Launch energy requirements are significantly lower than those for direct or ΔV-EGA trajectories, and deep-space ΔV requirements are also significantly lower than those for ΔV-EGA trajectories. These performance gains come at the expense of longer flight times, due to the additional planetary flybys in the inner solar system.

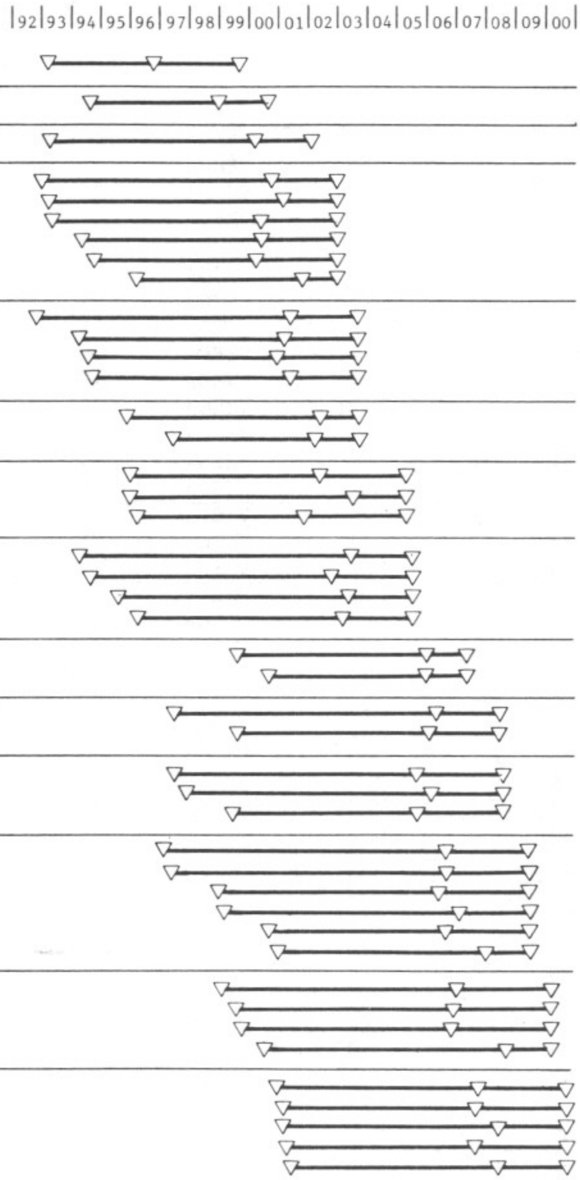
Several gravity-assist trajectories to Jupiter have been identified for each of the launch periods to Venus under consideration. The VEGA transfers would probably be preferred over VEEGA trajectories for new Jupiter missions due to their shorter flight times.

Gravity-assist trajectories to Saturn have also been identified for each of the launch periods to Venus under consideration through 2000. It has been demonstrated that while Jupiter flybys enhance performance and reduce flight times to Saturn, they are not mandatory to enable trajectories to Saturn. In fact, launch energy and ΔV requirements are fairly similar for VEEGA trajectories to either Jupiter or Saturn. However, flight times are generally longer in the inner solar system for trajectories to Saturn to achieve acceptable performance.

Table 10

TIMELINE FOR TRAJECTORIES TO COMETS

Comet	Trajectory	C_3	ΔV
1. Tempel 2	VEGA	14	3.6
2. Encke	VEGA	20	3.1
3. D'Arrest	VEEGA	19	2.6
4. Kopff	VEEGA	16	2.3
5.	VEEGA	15	1.9
6.	VEEGA	13	2.4
7.	VEGA	14	4.1
8.	VEGA	11	3.4
9.	VEGA	16	2.9
10. Wild 2	VEEGA	11	2.1
11.	VEGA	15	3.2
12.	VEEGA	11	2.7
13.	VEEGA	19	1.9
14. Encke	VEEGA	20	3.7
15.	VEGA	13	3.7
16. Tempel 2	VEEGA	23	2.7
17.	VEEGA	16	1.8
18.	VEEGA	10	3.0
19. Giacobini-	VEEGA	15	3.1
20. Zinner	VEEGA	13	3.8
21.	VEEGA	12	4.4
22.	VEEGA	17	3.8
23. Encke	VEEGA	24	4.1
24.	VEGA	15	4.3
25. Borrelly	VEEGA	14	3.0
26.	VEEGA	17	4.0
27. D'Arrest	VEEGA	15	2.3
28.	VEEGA	18	2.1
29.	VEEGA	23	2.9
30. Kopff	VEEGA	12	1.7
31.	VEEGA	16	2.4
32.	VEEGA	16	1.8
33.	VEEGA	12	2.2
34.	VEGA	20	2.7
35.	VEEGA	14	2.3
36. Wild 2	VEEGA	11	1.7
37.	VEEGA	14	1.7
38.	VEEGA	25	1.9
39.	VEEGA	14	2.4
40. Tempel 2	VEEGA	18	2.9
41.	VEEGA1	14	3.3
42.	VEEGA	22	1.9
43.	VEEGA	14	3.3
44.	VEEGA	17	1.5



C_3 = launch energy in km^2/s^2

ΔV = total postlaunch ΔV in km/s

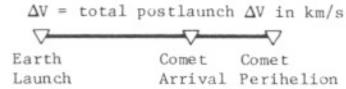


Table 11

TRANSFER GEOMETRY FOR TRAJECTORIES TO COMETS

	Comet	Launch Date	Trajec- tory	Earth-Venus Transfer (Type)	Venus-Earth Transfer (Type)	Earth-Earth Transfer	Earth-Comet Transfer (Type)
1.	Tempel 2	Feb 93	VEGA	II	II	--	II
2.	Encke	Aug 94	VEGA	IV	II	--	II
3.	D'Arrest	Mar 93	VEEGA	II	II	2-yr resonant	II
4.	Kopff	Nov 93	VEEGA	IV	II	Type III	I
5.		Feb 93	VEEGA	II	II	3-yr resonant	II
6.		Feb 93	VEEGA	II	II	2-yr resonant	II
7.		Apr 94	VEGA	III	II	--	II
8.		Sept 94	VEGA	II	III	--	I
9.		Jan 96	VEGA	IV	II	--	II
10.	Wild 2	Sept 92	VEEGA	IV	II	3-yr resonant	II
11.		May 94	VEGA	IV	III	--	I
12.		Sept 94	VEEGA	II	II	Type III	I
13.		Oct 94	VEEGA	II	II	2-yr resonant	II
14.	Encke	Dec 95	VEEGA	III	II	2-yr resonant	II
15.		Aug 97	VEGA	IV	II	--	II
16.	Tempel 2	Feb 96	VEEGA	I	III	Type II	II
17.		Feb 96	VEEGA	IV	II	2-yr resonant	II
18.		Mar 96	VEEGA	II	II	2-yr resonant	II
19.	Giaco-	Mar 94	VEEGA	IV	II	2-yr resonant	II
20.	bini-	Aug 94	VEEGA	I	II	3-yr resonant	II
21.	Zinner	Aug 95	VEEGA	III	II	2-yr resonant	II
22.		May 96	VEEGA	II	II	2-yr resonant	II
23.	Encke	Sept 99	VEEGA	II	II	2-yr resonant	II
24.		Sept 00	VEGA	IV	II	--	II
25.	Borrelly	Jun 97	VEEGA	IV	II	2-yr resonant	II
26.		July 99	VEEGA	II	II	2-yr resonant	II
27.	D'Arrest	Jun 97	VEEGA	III	II	3-yr resonant	II
28.		Nov 97	VEEGA	II	III	Type II	II
29.		Jun 99	VEEGA	I	II	2-yr resonant	II
30.	Kopff	May 97	VEEGA	III	IV	3-yr resonant	II
31.		Sept 97	VEEGA	IV	III	3-yr resonant	II
32.		Mar 99	VEEGA	III	II	Type III	II
33.		May 99	VEEGA	I	II	3-yr resonant	II
34.		Dec 00	VEGA	IV	II	--	II
35.		Mar 01	VEEGA	II	II	2-yr resonant	II
36.	Wild 2	Jan 99	VEEGA	III	II	3-yr resonant	II
37.		July 99	VEEGA	II	III	Type II	II
38.		Sept 99	VEEGA	II	II	Type III	I
39.		Sept 00	VEEGA	IV	II	2-yr resonant	II
40.	Tempel 2	Dec 00	VEEGA	IV	II	Type III	I
41.		Jan 01	VEEGA	I	III	3-yr resonant	I
42.		Jan 01	VEEGA	IV	II	2-yr resonant	II
43.		Feb 01	VEEGA	II	II	Type III	I
44.		Mar 01	VEEGA	II	II	3-yr resonant	II

Many trajectory possibilities to comets of high scientific interest have been identified through the end of the century. Several of the trajectory options to Kopff and Wild 2 for 1994 launches are being carried as candidate backup missions for the CRAF project. Usually, VEGA trajectories will provide shorter flight times than VEEGA trajectories, but it is possible for VEEGAs to provide both shorter flight times and improved performance to comets. Because of geometry considerations, missions to some comets such as Giacobini-Zinner and Borrelly may only be achieved for reasonable performance with VEEGA trajectories.

Have we identified all of the viable opportunities? The answer is probably not. While all of the ballistic opportunities may have been identified, utilization of deep-space maneuvers with different sequences of Venus, Earth, and Mars flybys may uncover new trajectory classes. When studying specific launch years to specific targets, the trajectories in this study should be used as starting points for future investigation. Spacecraft and launch vehicle considerations may require significant variations to the trajectories as presented here.

The classes of gravity-assist trajectories discussed in this report would also have application to missions to the other outer planets: Uranus, Neptune, and Pluto. VEEGA trajectories combined with outer planet gravity-assist flybys may provide a way to deliver massive payloads to the far outer planets. For these missions, the inner solar system trip time penalty would constitute a smaller percentage of the total flight time.

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