Small Spacecraft for Low-Cost Planetary Missions

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Small low-cost spacecraft offer the opportunity to carry out a variety of planetary exploration missions at modest cost as part of a sustained program. This study identifies scientifically valuable missions of modest cost that can be carried out by modifications of a single spacecraft design. These missions lend themselves to a continuing program of essentially constant funding level. Such a program could involve several launches spread over a period of 10 to 15 years at roughly two-year intervals. The stability offered by relatively constant funding, frequent launches, and the return of data in a more nearly constant fashion than is typical of planetary science in the recent past would greatly enhance solar system exploration and sustain a level of interest between the less frequent large programs, which require a major national commitment.

The ability to construct capable, reliable spacecraft for modest cost and adapt them to the various missions without a major redesign is critical. Today's developing small spacecraft technology offers that promise. Several typical candidate spacecraft have been identified and used as a basis for this study. Concurrently, several worthwhile planetary science missions have been identified. With these inputs, a candidate program plan has been developed to meet the criteria of constant funding, reasonably spaced launches, and worthwhile science objectives.

INTRODUCTION

Three elements are key to a viable small missions program: (1) scientific value, (2) minimal cost, and (3) sustainability. To satisfy all three of these requirements, the program must be constructed according to several guidelines. Among these guidelines are the following, which also served as constraints for this study:

- The program must contain strong science, which is consistent with stated exploration goals and is supported by the appropriate science working groups.
- Costs must be constrained to less than $100 million per mission. Although launch vehicles and flight operations are not included, every effort has been made to minimize those costs as well.
- A stable, sustainable program should be created, with one management organization for all missions.
- Hardware costs should be minimized to meet mission cost objectives. Possible approaches to this situation include using existing hardware (spacecraft and instrumentation), designing new spacecraft composed of off-the-shelf parts, and imposing design limitations such as solar powered spacecraft only.
- One to three instruments are included on each spacecraft.

- On average, the desired launch frequency is every other year.
- Joint missions with other Divisions of the Office of Space Science and Applications should be considered.

Five candidate missions were selected for further examination and for inclusion in a small planetary missions program to be launched over the period from 1994 to 2010. These five candidates, discussed in detail later in this paper, are:

- Lunar Orbiters (3 missions)
- Venus Atmospheric Probe
- Near-Earth Asteroid Rendezvous
- Comet Coma Sample Return
- New Comet Flythrough

The first four are part of the mission set developed by the NASA Solar System Exploration Committee in defining its Core Program. An alternative to this approach is to construct a program that focuses on a particular target or family of targets; for example, the near Earth asteroids might be an ideal target for a small missions program.

SPACECRAFT OPTIONS

A variety of large and small spacecraft could be considered for use in a planetary small missions program; candidates are summarized in Table 1. Even though the primary low-cost focus of this program would seem to dictate small spacecraft, repeat purchases of larger spacecraft already in production (e.g., the DMSP and DSCS III spacecraft built by General Electric Astro Space Division) might possibly offer attractive options for some missions. Most large spacecraft, however, are expensive and may not fit within the budget constraints of a small planetary missions program unless the cost of modification is low. On the other hand, since these spacecraft are large and of substantial capacity, modest changes could be made at a cost that could be competitive with smaller spacecraft, which may require more extensive modifications.

Several small spacecraft of the type sometimes generically referred to as "Lightsats" are being produced or are planned to be in production within the time frame of interest. These Lightsats range from "Getaway Special" canister-sized units weighing about 150 kg up to spacecraft of 1 m in diameter weighing about 400 kg. Table 1 describes five such spacecraft. Generally, these spacecraft are more limited in capacity, especially power, than the larger types discussed above. This limitation tends to aid in keeping the total cost low, since the original spacecraft is less costly, and the number of expensive instruments that it may carry is sharply limited. A potential problem with small spacecraft is that they are often designed for simplicity, especially in attitude control, using methods applicable only at Earth. Thus, by the time all the required changes are made for interplanetary flight, only the nameplate of the original spacecraft survives. In such a case, the cost might equal, or exceed, that of a new spacecraft, or a more sophisticated spacecraft.

A third option is to build the spacecraft from scratch to match the mission. With the variety of space-qualified hardware and high-quality non-space hardware available, assembling a new spacecraft for a specific mission is surprisingly easy and quick. Costs need not be high as long as requirements are kept within

TABLE 1: SURVEY OF SPACECRAFT FOR PLANETARY SMALL MISSIONS

	LARGE SPACECRAFT			SMALL SPACECRAFT					CUSTOM
	DMSP BLK 5D-2	DMSP BLK 5D-3	DSCS III	GAS CAN SIZE	SMALL EARTH ORBIT	SPACE PHYSICS EXPLORER	GS-50	GS-200	DELTA STAR
Dimensions (cm)	Not available	Not available	275 cm d 395 cm h	61 cm d 36 cm h	96 cm d 89 cm h	75 cm d 36 cm h	43 cm d 67 cm h	117 cm d 178 cm h	Not available
Dry Mass (kg)	591	771	423	63.5	113	87	35 (?)	200	1558
Power (w)	Solar arrays	Solar arrays	Solar array 1240w BOL; 980w @ 10 years	Solar, 80w	Solar, 90w	Solar, 50w; 100w with deployment	Solar, 10w	Solar, 85w	Solar, 583w avg; 3 batts @ 35 a-hr
Communications	S-band 2237.5 MHz	S-band 2237.5 MHz	S-band (SGLS) X-band	G-STDN or SGLS	G-STDN or SGLS 50w	X-band DSN, 10w	G-STDN, 10w	UHF 2w; X-band 18w	2 S-band omni's, 2237.5 MHz
Propulsion	16 kg Hyd 2.3 kg GN_2 STAR 37S	22 kg Hyd 3.6 kg GN_2 STAR 37 FP	276 kg Hyd 16-4N Thrusters	None	132 kg Hyd	36 kg Hyd or 82 kg biprop N_2O_4/N_2H_4	None	None	Hydrazine, 16-22N Thr's 4-150N Thr's GN_2
Attitude Control	Inertial (strap down) w/star sensor	Inertial (strap down) w/star sensor	3-axis Earth reaction wheel	3-axis	3-axis 1 deg	Spin stab despun plt or 3-axis mom wheels & thrusters	3-axis mag torq; horiz sensor	3-axis mag torq; sun & horiz sensors	Inertial (strap down) w/command update
Data Storage	5 Tape recorders	5 Tape recorders	None	100 Mb	75 Mbytes	256 Mb	Not available	200 Mbytes	In science module
Manufacturer	GE Astro	GE Astro	GE Astro	Defense Sciences	Defense Sciences	Ball Aerospace	Globesat	Globesat	McDonnell Douglas

reasonable limits, and firm direction is provided. A recent example is the Delta Star spacecraft built by McDonnell-Douglas Space Systems Company for the Strategic Defense Initiative Organization. Although its neither small nor especially inexpensive, Delta Star can be considered a low-cost spacecraft since such a special-build large vehicle with the same capability would probably cost two to five times as much if developed in the conventional NASA or Air Force manner. Delta Star is not considered a candidate for a small missions program since it is a special build design. Rather, it is presented as an example of an approach that, if conducted on a smaller scale, might be applicable.

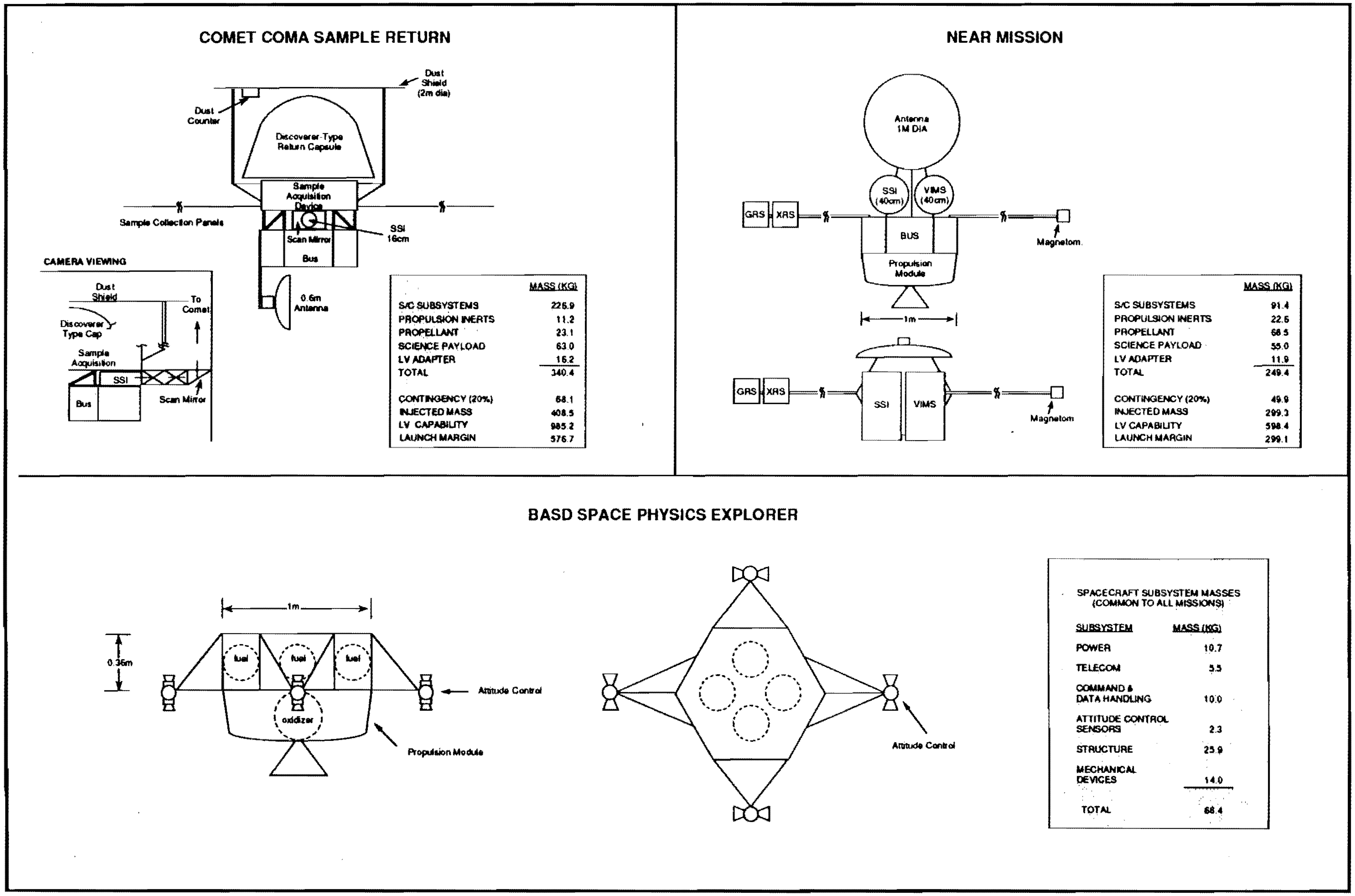
For the purposes of this study, the Ball Aerospace (BASD) Space Physics Explorer was selected as the basic spacecraft since it appears to require the least amount of modification to perform the full mission set. Figure 1 provides a general profile of the spacecraft configuration and dimensions. The Space Physics Explorer is a six-sided spacecraft with body-mounted solar panels capable of supplying up to 50 W of power. An additional 50 W can be supplied by adding a deployable array. The diameter is large enough to accommodate remote sensing instruments mounted on top of the bus and can provide up to 256 Mbytes of data storage. Although the BASD spacecraft is spin-stabilized, it could be modified to an axis-stabilized configuration in order to accommodate the lunar and asteroid missions. Figure 1 also illustrates how the spacecraft might be configured for two of the missions under consideration.

LAUNCH VEHICLES

Among currently available U.S. launch vehicles, four are considered potential candidates for the types of missions discussed here: Delta II, Titan II, Pegasus, and Scout. Other launchers, generally lower in cost, are planned by various entrepreneurial companies (e.g., American Rocket Company, Pacific American Launch Systems Inc., and Space Services Inc.); however, availability and performance of these launchers are not fully defined at this time and they are not considered in this discussion. If such launchers do become available and prove themselves reliable, their applicability to any small planetary mission should be reconsidered.

The performance of the candidate launch vehicles to a 185 km (100 nmi) parking orbit is presented in Table 2. The Delta IIs come in a three-stage version, which is normally used for high energy missions. The 7925 Delta II has the highest performance of the four vehicles considered with a mass to orbit of 4,989 kg. The Titan II, so far, has only been flown in the basic two-stage mode without strap-ons. In this configuration, its performance is almost 1,500 kg less than the 6925 Delta II. The Titan II's only current launch capability is from Vandenberg Air Force Base into polar orbit. There is interest in providing a launch capability from Cape Canaveral Air Force Station but plans are uncertain. Since this type of launch would be the capability of interest, performance out of that location is presented in Table 2. Plans exist to equip the Titan II with solid rocket strap-ons and a third stage similar to the Delta second stage. This configuration would provide a capability slightly higher than the 6925 Delta II but lower than the 7925 Delta II.

The Scout is a proven launch vehicle but its performance to a 185 km orbit is only a fraction of that of the Titan II and Delta II. The main advantage over the Scout's larger cousins is the variety of launch platforms available to



Comet Coma Sample Return

	MASS (KG)
S/C SUBSYSTEMS	226.9
PROPULSION INERTS	11.2
PROPELLANT	23.1
SCIENCE PAYLOAD	63.0
LV ADAPTER	16.2
TOTAL	340.4
CONTINGENCY (20%)	68.1
INJECTED MASS	408.5
LV CAPABILITY	985.2
LAUNCH MARGIN	576.7

NEAR Mission

	MASS (KG)
S/C SUBSYSTEMS	91.4
PROPULSION INERTS	22.5
PROPELLANT	68.5
SCIENCE PAYLOAD	55.0
LV ADAPTER	11.9
TOTAL	249.4
CONTINGENCY (20%)	49.9
INJECTED MASS	299.3
LV CAPABILITY	598.4
LAUNCH MARGIN	299.1

SPACECRAFT SUBSYSTEM MASSES (COMMON TO ALL MISSIONS)

SUBSYSTEM	MASS (KG)
POWER	10.7
TELECOM	5.5
COMMAND & DATA HANDLING	10.0
ATTITUDE CONTROL SENSORS	2.3
STRUCTURE	25.9
MECHANICAL DEVICES	14.0
TOTAL	68.4

Figure 1: The BASD Space Physics Explorer and configurations for CCSR and NEAR

it. If desired, it can be launched from the San Marco platform off Kenya into an equatorial orbit. Pegasus is a newly developed air-launched vehicle with performance comparable to the Scout. Its maiden flight is scheduled for the fall of 1989. Use of air launch frees the vehicle from limited launch inclinations imposed by the geographic location of the launch platform, and allows a variety of launch inclinations, including equatorial, to be achieved. In their current configurations, both Scout and Pegasus lack the capability to perform the candidate missions. An uprated version of Scout is being planned that would offer improved performance. While nothing is known about future plans for Pegasus, an upgraded version seems probable.

TABLE 2: LAUNCH VEHICLE PERFORMANCE TO 185 KM ORBIT

LAUNCH VEHICLE	PAYLOAD (kg)	INCLINATION (deg.)	COST ($M)
Delta II 6925	3946	28.5	~ 50
Delta II 7925	4989	28.5	~ 50
Titan II (basic 2-stage)	2472	28.5	~ 50
Titan II (3-stage w/strap-ons)	4263	28.5	?
Pegasus	454	0.0	7-10
Scout	454-499	0.0	15-20

Both the 6925 Delta II and Titan II can perform any of the missions that make up the plan in this study. Since the cost of the Delta II is nearly equal to that of the Titan II, the Delta II was selected as the primary launch vehicle on the basis of launch pad availability at Cape Canaveral. Assuming that the Delta II is the primary launch vehicle, a breakdown of the spacecraft mass for each of the missions considered is presented in Table 3.

TABLE 3: SPACECRAFT MASS* BREAKDOWN BY MISSION

	LM1	LM2	LM3	NEAR	NCF	CCSR	VAP
S/C Systems	84.4	84.4	84.4	91.4	80.1	226.9	70.5
Propulsion Inerts	23.3	22.9	23.2	22.6	9.8	11.2	11.5
Propellant	73.8	70.8	73.2	68.5	12.9	23.1	24.7
Science Payload	31.0	26.0	25.0	55.0	34.0	63.0	307.0
LV Adapter	10.4	10.0	10.3	11.9	6.8	16.2	20.6
Total	222.9	214.1	216.1	249.4	143.6	340.4	434.3
Contingency (20%)	44.6	42.8	43.2	49.9	28.7	68.1	86.9
Injected Mass	267.5	256.9	259.3	299.3	172.3	408.5	521.2
LV Capability	1055.9	1055.9	1055.9	598.4	645.3	985.2	877.9
Launch Margin	788.4	799.0	796.6	299.1	473.0	576.7	356.7

*Note: All masses are in kg's
LV=Launch Vehicle; LM=Lunar Mission; NEAR=Near-Earth Asteroid Rendezvous; NCF=New Comet Flythrough; CCSR=Comet Coma Sample Return; VAP=Venus Atmospheric Probe

LUNAR MISSIONS

The Moon is considered to be a relatively simple differentiated silicate system that has preserved nearly 4 billion years of solar system history. It is, therefore, probably the best place in the Solar System to study the processes that affected the formation of other silicate bodies early in their history. The Moon also serves as a key to understanding Earth's early history, since Earth's origin and evolution is closely tied to lunar genesis. Although our current knowledge of the Moon is probably more detailed than any other planetary body, major gaps exist in our understanding of lunar science. Only 80 percent of the lunar surface has been mapped at low resolutions, and the poles are virtually unknown. Knowledge of its geochemical composition is not accurate enough to permit detailed conclusions to be drawn about specific regions of the Moon. Also, as a potential extraterrestrial resource, it is important to obtain a detailed understanding of the structure and composition of the lunar crust.

Major objectives for a lunar mission are[1]: (1) determine the elemental and mineralogical composition of the lunar surface, (2) identify the regional extent of rock types, including any new lithologies, (3) assess global resources including a search for volatiles at the poles, (4) measure the global figure, surface topography, and global gravity field, (5) measure the orientation of regional surface magnetic fields as a function of age, and (6) estimate current surface heat-flow.

Most of these objectives can be met by using three small, dedicated orbiters. The strategy is to take a major mission like the Lunar Observer (LO) and divide its instrument complement into three separate missions. Concern exists, however, that in dividing up the instruments in this manner, precise data correlation and synergism among the instruments might be reduced or lost (R. Pepin, personal communication). The first mission would map the surface elemental composition and measure any surface magnetic fields using an X-ray/gamma-ray spectrometer and magnetometer. The second mission would focus on mapping the surface mineralogy using a visual-infrared mapping spectrometer and provide additional observation of surface magnetic fields. A high-resolution imaging system and a radar (or laser) altimeter to characterize surface morphology and topography would fly on the third mission. Table 4 outlines the instrument characteristics for each lunar mission. This payload would depend heavily upon inheritance from the Mars Observer Mission[2].

The spacecraft, with an attached solid rocket motor, would be delivered into a 185 km circular parking orbit. At a suitable point, the solid motor is fired to place the spacecraft on a minimum energy lunar transfer trajectory. The spacecraft on-board propulsion unit is used to trim the trajectory. The transfer trajectory is shaped to place the lunar approach asymptote over one of the poles. As the spacecraft approaches periapsis, the on-board propulsion system is fired to place the spacecraft into an initial 100 km x 10,000 km orbit. After tracking to ascertain proper inclination, etc., the propulsion system is used to lower the orbit to 100 km circular after any required corrections are made. While the spacecraft is in its initial elliptical orbit, gamma-ray spectrometer calibration (if applicable) is conducted and magnetometer and/or electron reflectometer data (if applicable) are gathered. This period may be extended for science purposes.

TABLE 4: INSTRUMENT COMPLEMENT OF LUNAR MISSIONS

INSTRUMENT	MASS (kg)	POWER (W)	DATA RATE (bps)	LM1	LM2	LM3
X-Ray Spectrometer	11	10	(2000)	√		
Gamma-Ray Spectrom	13	10		√		
Imager	10	7	55,000			√
VIMS	19	12	32,000		√	
Laser Altimeter	15	28	720			√
Magnetometer	2	3	320	√	√	
Electron Reflectom	5	5	300	√	√	
			TOTAL MASS (kg)	31	26	25
			POWER (w)	28	20	35
			DATA (kbps)	4.6	32.6	10.8

Once established in the circular orbit, surface observations will begin. Because of the irregular shape of the Moon, the orbit is unstable and frequent correction burns will be required, probably at least weekly. In order to ensure detailed coverage, especially for the gamma-ray spectrometer, orbital operating lifetime is to be at least one year.

VENUS ATMOSPHERIC PROBE

The U.S. Pioneer Venus and the U.S.S.R. Venera and Vega missions have combined to provide a basic data base on the composition, structure, and dynamics of the Venusian atmosphere. However, as is often typical of reconnaissance and early exploration missions, only some questions regarding Venus's atmosphere were answered while many others were raised. These questions can be addressed in part by an atmospheric probe instrumented for precise abundance measurements down to sub-parts per billion levels. Verification of large Ar abundance, low (Earth-like) Ne/Ar ratio, and hints of low (sun-like) Kr/Ar and Xe/Ar ratios from the presently very uncertain Kr and Xe data, is needed. Considerably more accurate values for $^{20}Ne/^{22}Ne$, $^{36}Ar/^{38}Ar$, $^{15}N/^{14}N$, $^{13}C/^{12}C$ and D/H ratios, and determination of the still unmeasured $^{21}Ne/^{22}Ne$ ratio and Kr and Xe compositions, are required to place constraints on current theories for the origin and evolution of planetary atmospheres. The oxidation state of the lower atmosphere, H_2 and water abundances, and density profiles for sulfur compounds (H_2S, COS, and sulfur dioxide) have also been identified as major questions for resolution as a result of earlier missions[1].

The primary objective of a Venus atmospheric probe mission is to determine the composition of the atmosphere of Venus. It is important to measure with precision the abundances and isotopic compositions of the five noble gases, nitrogen, carbon, and hydrogen. To accomplish this, the probe will be equipped with: (1) a neutral mass spectrometer to measure chemical composition and isotope ratios, (2) a gas chromatograph to provide atmospheric profiles of trace constituents including the noble gases, sulfur compounds, and water, and (3) an atmospheric structure instrument designed to measure molecular mass, pressure, temperature, and density profiles and other parameters that characterize the dynamics of Venus' atmosphere. Table 5 outlines the instrument payload; its heritage is primarily the Pioneer Venus Large Probe[3].

TABLE 5: INSTRUMENT COMPLEMENT FOR VENUS ATMOSPHERIC PROBE

INSTRUMENT	MASS (kg)	POWER (W)	DATA RATE (bps)	HERITAGE
Mass Spectrometer	11	14	40	PVLP
Gas Chromatograph	7	42	30	PVLP
Atmos. Structure Instrument	3	5	74	PVLP
TOTALS	21 kg	61 w	144 bps	

The Venus Atmospheric Probe would be delivered to a Venus transfer orbit by a Delta II 6925 three stage vehicle. About 20 to 30 days before Venus arrival, the spacecraft would maneuver to the required attitude and deploy the probe. Probe targeting requirements include not only locating the probe near the equator - at least 20° into daylight from the terminator - but also delaying the atmospheric entry of the carrier spacecraft by about one hour after probe atmospheric entry. The separation velocity change would be about 0.5 m/sec and would be accomplished using a spring mechanism. Probe operation would be initiated by a timer several minutes before entry. During entry and parachute descent, data would be transmitted via an S-band link at about 100 bps relayed directly back to Earth. The spacecraft would also enter the Venusian atmosphere and, having no heat shield, be destroyed. If desired (and affordable), limited instrumentation dealing with the upper atmosphere could be carried on this vehicle. If this instrumentation is carried, the time difference allows the probe entry phase to be complete before carrier spacecraft data acquisition and transmission begins.

NEAR-EARTH ASTEROID RENDEZVOUS

Near-Earth asteroids are a diverse group of objects that are related in an unknown way to comets, main-belt asteroids, and meteorites. They are also the most accessible neighbors to the Earth besides the Moon. Near-Earth asteroids are important to solar system exploration for five reasons[4]: (1) they provide a key to understanding the relationship of meteorites to primitive bodies, (2) they preserve clues regarding the makeup and building blocks of Earth-like planets, (3) due to their small size and gravity, these asteroids may reveal surface processes and characteristics significantly different from those studied on larger, more massive bodies, (4) they have probably influenced both the geological and biological evolution of Earth, and (5) due to their proximity to Earth, they provide optimal targets for future sample return and space utilization missions.

The science objectives of a Near-Earth Asteroid Mission are to determine[4]: (1) bulk properties such as size, volume, mass, gravity field, and spin rate, (2) surface properties such as geochemical composition, geology, morphology, and surface texture, (3) internal properties such as mass distribution and any magnetic fields, (4) any possible near-asteroid gas and dust, and (5) the nature of the asteroid's interaction with the solar wind.

The strawman science instrument payload (Table 6) includes: (1) an imaging system to determine surface physical characteristics, size, shape, rotation, and volume; (2) a spectral mapper (VIMS) to identify mineral phases of surface materials and determine their spatial extent; (3) an x-ray and gamma-ray spectrometer to globally map surface elemental composition; (4) radio science to provide mass determination to within 1% and determine gravity harmonics to a level sufficient to identify any major internal density inhomogeneities; and (5) a magnetometer to detect any surface magnetic fields and their interaction with the solar wind.

TABLE 6: INSTRUMENT COMPLEMENT OF NEAR-EARTH ASTEROID RENDEZVOUS

INSTRUMENT	MASS (kg)	POWER (W)	DATA RATE (bps)	HERITAGE
Imager	10	7	55,000	MO/LO
X-Ray Spectrometer	11	10	(2,000)	PIDDP
Gamma-Ray Spectrom	13	10		MO/LO
VIMS	19	12	32,000	MO/LO
Magnetometer	2	3	320	MO/LO
Radio Science	-	-	-	MO/LO
TOTALS	55 kg	42 w	89.3 kbps	

Following an interplanetary cruise phase that may range in duration from just over one year to nearly three years, the spacecraft will encounter the asteroid. The imaging system will be used to acquire the asteroid and image it against the star background for navigation. The imager should be able to acquire the asteroid prior to rendezvous, allowing final course corrections to bring the rendezvous point relatively close to the asteroid. If the asteroid is not acquired early, the spacecraft will rendezvous with the most probable location of the asteroid, biased toward the sunward side, and a search pattern will be initiated using the imager.

Once rendezvous is achieved, initially at a distance of a few tens of kilometers, the spacecraft will proceed with long-range observations. This stage will be followed by a very small propulsion burn to send the spacecraft on a trajectory that passes within a few kilometers of the asteroid. Several such flybys at steadily decreasing periapsis altitudes would be carried out to observe and, from very accurate tracking, to determine the gravitational characteristics of the asteroid. The minimum stable orbit distance can then be defined, and the spacecraft will enter that orbit for long-term observations. Eccentricity, altitude, and inclination may be changed from time to time as long as propellant lasts. When propellant is nearly depleted, the spacecraft could be targeted for a landing on the asteroid to serve as a long-term observing station.

COMET COMA SAMPLE RETURN

Comets, the most primitive bodies in the solar system; their origins that lie in the outer fringes of the solar sphere of influence. They are also well-preserved icy relics of the conditions that pervaded during the early stages of accretion of the solar nebula. As such, they are likely to be the best source of obtainable samples of the original material from which the solar system was formed, and may provide a cosmochemical record of conditions in the interstellar medium and primordial solar nebula.

The scientific objectives of the Comet Coma Sample Return mission are to obtain samples of the volatile and non-volatile constituents of the coma during a fast flythrough, and return them to Earth for analysis. In addition, the spacecraft will determine the densities of coma materials along the flight path. To meet these objectives, it will be necessary to adhere to the following collection requirements[1]:

- For dust samples, (1) collect at least three dust particles, intact, with diameters ranging from 0.5 to 1.0 mm, and (2) collect a minimum of one hundred smaller particles with diameters ranging from 50 to 200 micrometers.

- For gas samples, obtain a total fluence of at least 10^5 to 10^6 gas molecules per square centimeter.

- For all samples, limit contamination of the samples obtained during the mission to one contaminant atom to each 100 sample atoms, and design the experiment to facilitate handling, cleaning, and safe distribution to multiple laboratories.

In addition to the dust/gas collection device, a dust counter will be required to determine the dust density along the flight path. An imaging system will also be required to provide terminal navigation for close-in targeting of the spacecraft. The imager also will serve to determine the size, shape, rotational properties and location of the nucleus. A summary of the payload is provided in Table 7.

TABLE 7: INSTRUMENT COMPLEMENT FOR COMET COMA SAMPLE RETURN

INSTRUMENT	MASS (kg)	POWER (W)	DATA RATE (bps)	HERITAGE
Dust/Gas Collector	50	50*	-	NEW
Imager	7	7	20,000	GIOTTO
Dust Counter	3	3	800	GIOTTO
TOTALS	60 kg	60 W	20.8 kbps	

* required only during deployment and retraction

The spacecraft system (see Figure 1) would be launched, from an Earth parking orbit, on the required intercept trajectory. The complete system would include a spacecraft with instrument package, sample gathering mechanism, and Earth entry capsule. The assembly would probably be spin-stabilized, although 3-axis stabilization would be acceptable. During outbound cruise, only modest course corrections are required. Approaching the comet, but still at considerable distance, for example 500,000 km or the maximum detection range, the imager would be used to image the comet against the star background for navigation purposes. This process would continue, with course corrections as required, until shortly before encounter in order to ensure sampling in the desired region of the coma.

Prior to entering the coma, the collector mechanism would be deployed. The imaging system and dust counter would be active on final approach and during the flythrough. After exiting the coma, the collector would be folded and the sample bearing surfaces stowed in the entry capsule. Imaging would probably continue periodically during the outbound leg.

During cruise back to Earth, course corrections would be made as required to ensure accurate targeting. Ground-based tracking should be adequate, although the imager could be used for optical correction. About 200 m/s is available for course correction. This rather generous amount reflects uncertainty regarding the comet's exact orbit in the presence of non-gravitational forces. Several hours prior to entry, the entry capsule would be separated from the spacecraft. (For a non-spinning bus, spinup would be required.) Entry would be purely ballistic at an angle of 30° to 50° below horizontal. Although g-loads up to 200 g will be experienced by the capsule, this should not be a problem for a properly designed system. At this steep angle, targeting accuracy at parachute opening should be essentially the same as B-plane accuracy or only slightly poorer.

NEW COMET FLYTHROUGH

"New" comets are either those objects with orbital periods on the order of thousands of years or more or are newly perturbed into the inner solar system. Consequently, these comets are likely to be less eroded and to retain a greater amount of their original constituent gases and material than those comets with orbital periods less than 100 years (i.e., periodic comets).

The scientific objectives of the New Comet Flythrough would be similar to those for CRAF at its target comet. The objectives include: (1) determining the composition and physical state of the cometary nucleus, and (2) investigating the nature and composition of the cometary atmosphere and how it interacts with the solar wind.

The baseline scientific instrument payload (Table 8) for this mission is: (1) an imaging system to characterize the shape, size, and morphology of the cometary nucleus, (2) a dust counter and ice/dust analyzer to characterize the bulk elemental composition and distribution of cometary ice and dust grains, (3) a neutral gas/ion mass spectrometer to analyze the chemical composition of the neutral gas and low-energy ions within the coma, and (4) a magnetometer to monitor the comet's interaction with the solar wind and characterize the magnetic fields in the cometary atmosphere and ionosphere.

This mission depends upon early detection of an incoming new comet and rapid determination of its orbit. This aspect is beyond the scope of this study but must play a role in the program plan. The overall goal is to be launch ready about 30 days after target identification. Whether the launch actually occurs at that time is a function of the target orbit, encounter geometry, and other factors. Once the spacecraft is launched, on-board propulsion will be used to correct the orbit for intercept and to control encounter geometry. On-board imaging of the comet against the star field will provide navigational updates during the final few weeks of the mission.

TABLE 8: INSTRUMENT COMPLEMENT OF NEW COMET FLYTHROUGH

INSTRUMENT	MASS (kg)	POWER (W)	DATA RATE (bps)	HERITAGE
Imager	10	7	20,000	MO/LO
Neutral Mass/Ion Mass Spectrometer	9	10	1,000	CRAF
Dust Counter	3	3	800	GIOTTO
Ice/Dust Analyzer	9	10	5,000	CRAF
Magnetometer	3	4	400	CRAF
TOTALS	34 kg	34 w	27.2 kbps	

Because of a probable science desire to approach the nucleus rather closely and to penetrate the zone of parent molecules, survival of the spacecraft through closest approach is questionable at best. Therefore, an operational constraint is that all data be returned in real time. Data storage would probably be incorporated to accommodate replay of the post encounter data if the spacecraft survives. This is to ensure against impact upsets that might cause loss of downlink lock without destroying the spacecraft.

Observations with the imaging equipment would be conducted periodically from the time the spacecraft sees the comet, becoming virtually continuous during the final hours. The magnetometer would be operating in a continuous mode. The other instruments would be activated shortly before entering the coma. Assuming the spacecraft survives, this mode would continue until exiting the coma. Periodic imaging of the comet would continue during the post-encounter phase of the mission.

COST AND PROGRAMMATIC ISSUES

The proposed small missions program would begin in the 1991 fiscal year, and would include seven separate launches. The complete program spans 17 fiscal years. The sequence begins with the three lunar missions launching in 1994, 1996, and 1998. (See Figure 2 for operations profiles for each mission.) Costs and development time for the first mission include a spare spacecraft, to be carried as a rolling spare throughout the program. Next in the queue is a rendezvous with a near-Earth asteroid, 1982 DB. The mission would be launched in January 2000. Each of these first four missions would continue operating at its target for a nominal one-year period.

The New Comet Flythrough would be planned for launch between 2001 and 2009, anticipating discovery of a suitable target. The Venus probe is planned to launch in the November 2005 opportunity. Finally, a February 2007 launch to

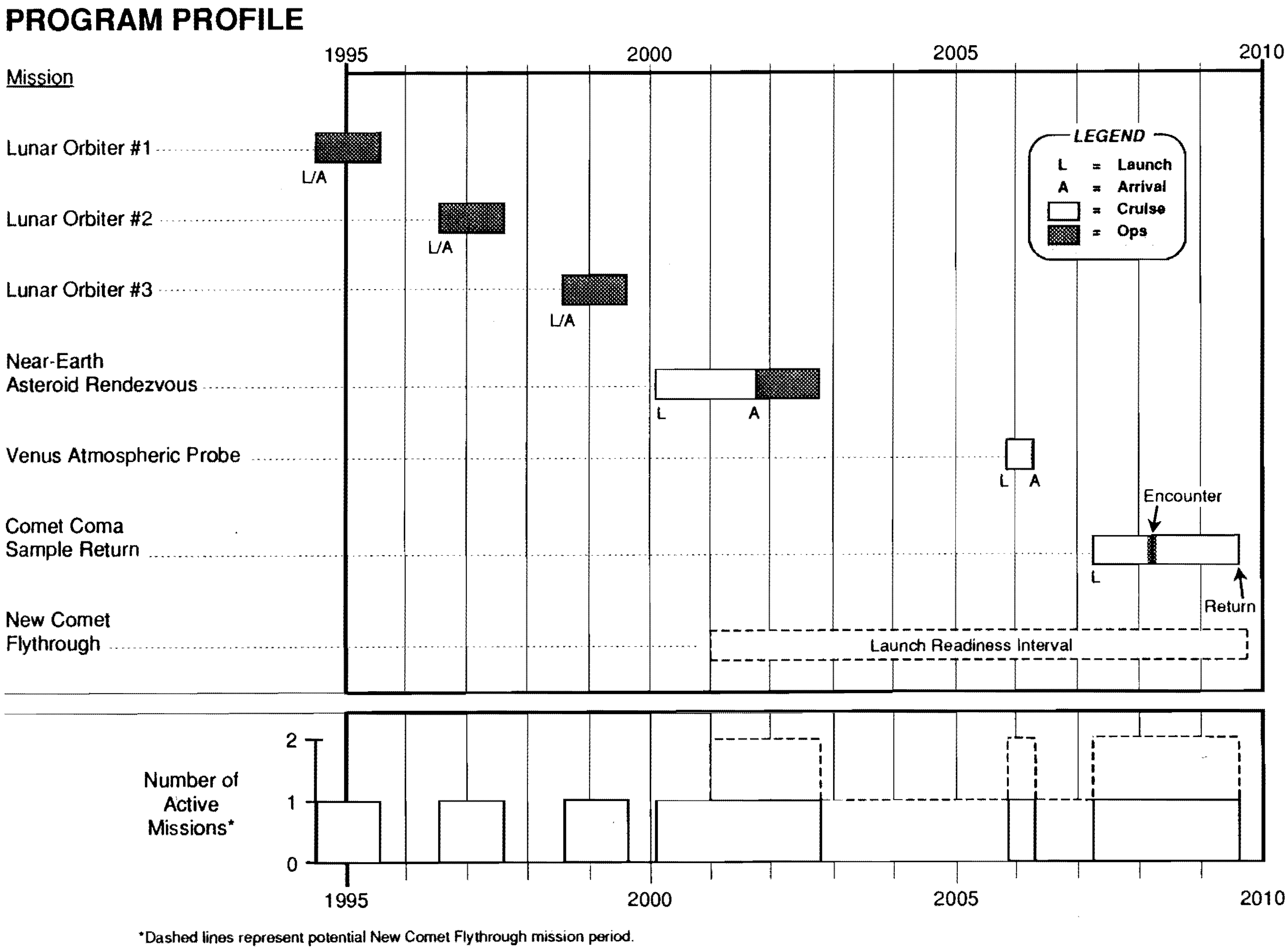


Figure 2: Profile for planetary small missions program through the year 2010

comet Wirtanen would return a coma sample to Earth in mid-2009. Table 9 lists several options that could be used for the asteroid, Venus, and comet coma sample return missions; since the New Comet Flythrough depends on a target of opportunity, no targets are listed for that mission.

TABLE 9: SMALL MISSION OPTIONS

MISSION	LAUNCH DATE	TARGET	INJECTION ENERGY, C_3 km^2/s^2	VELOCITY DATA km/s
NEAR	January, 2002	1982 DB	22.3	PL ΔV = 0.308
NEAR	December, 2000	1982 XB	27.9	PL ΔV = 1.453
NEAR	May, 2002	Anteros	37.8	PL ΔV = 0.952
VAP	May, 2007	Venus	6.0	AR V_{HP} = 3.8
VAP	December, 2008	Venus	7.2	AR V_{HP} = 4.0
CCSR	January, 2008	Neujmin 2	16.4	ENC V_{HP} = 11.4
CCSR	December, 2008	Howell	10.7	ENC V_{HP} = 12.5

PL=Post-launch, AR=Arrival, ENC=Encounter
NEAR=Near-Earth Asteroid Rendezvous, VAP=Venus Atmospheric Probe,
CCSR=Comet Coma Sample Return

Table 10 summarizes the cost estimates developed for this mission set using SAIC's Planetary Cost Estimation Model. These costs include development of one flight unit and initial launch plus 30-day operations only, consistent with typical Class C estimates. Only the first lunar mission allows for a full spare development, however, block purchases are used wherever possible. Note that the bottom-line costs shown in table 9 exclude three items: (1) $156 million for science instrument development, (2) $58 million for the Venus probe and spare, and (3) $60 million for the comet coma sample return reentry capsule and spare. The development of instruments not already available from other programs could be funded by NASA R&A money. The probe and reentry capsule could be built by a partner organization. With these assumptions, the average expenditure for the program is $45 M per year (FY89 $) over 17 fiscal years (Figure 3). More expensive missions can be kept within funding limits by considering either international cooperation or longer intervals between missions.

CONCLUSIONS

This study has shown that valuable planetary science, using missions that might not otherwise be funded as single projects, can be accomplished within the bounds of a small missions program, and that these missions could be done more frequently, thus increasing the overall science return. The feasibility of the concept is confirmed by technical and programmatic analyses of the strawman mission set. These are based on the Core Program missions initially recommended by the NASA Solar System Exploration Committee with the addition of a new comet flythrough mission.

Single, low-cost spacecraft requiring only modest modifications to satisfy the requirements of those missions examined, are available. Examples of such spacecraft include the Ball Aerospace Space Physics Explorer. Currently

TABLE 10: PLANETARY SMALL MISSIONS COST ESTIMATE IN FY89 DOLLARS

	LUNAR MISSIONS 1*	2	3	ASTEROID RENDEZVOUS	NEW COMET	VENUS PROBE	COMET COMA SAMPLE RETURN
HARDWARE	102	38	40	47	55	83	114
PROJECT MANAGEMENT	8	3	3	4	4	7	9
L + 30 DAYS OPS	8	3	3	3	4	6	8
SCIENCE DATA ANALYSIS	4	2	3	3	1	3	1
Subtotal	122	46	49	57	64	99	132
CENTER RESERVE @ 30%	37	14	15	17	19	30	40
Subtotal	159	60	64	74	83	129	172
HQ RESERVE @ 15%	24	9	10	11	12	19	26
TOTAL	183	69	74	85	95	148	198
Less probe or capsule						(41)	(51)
						107	147
R&A SUPPORT FOR INSTRUMENT DEVELOPMENT	34	18	20	-	61	-	23

*Assume rolling spare built with first orbiter

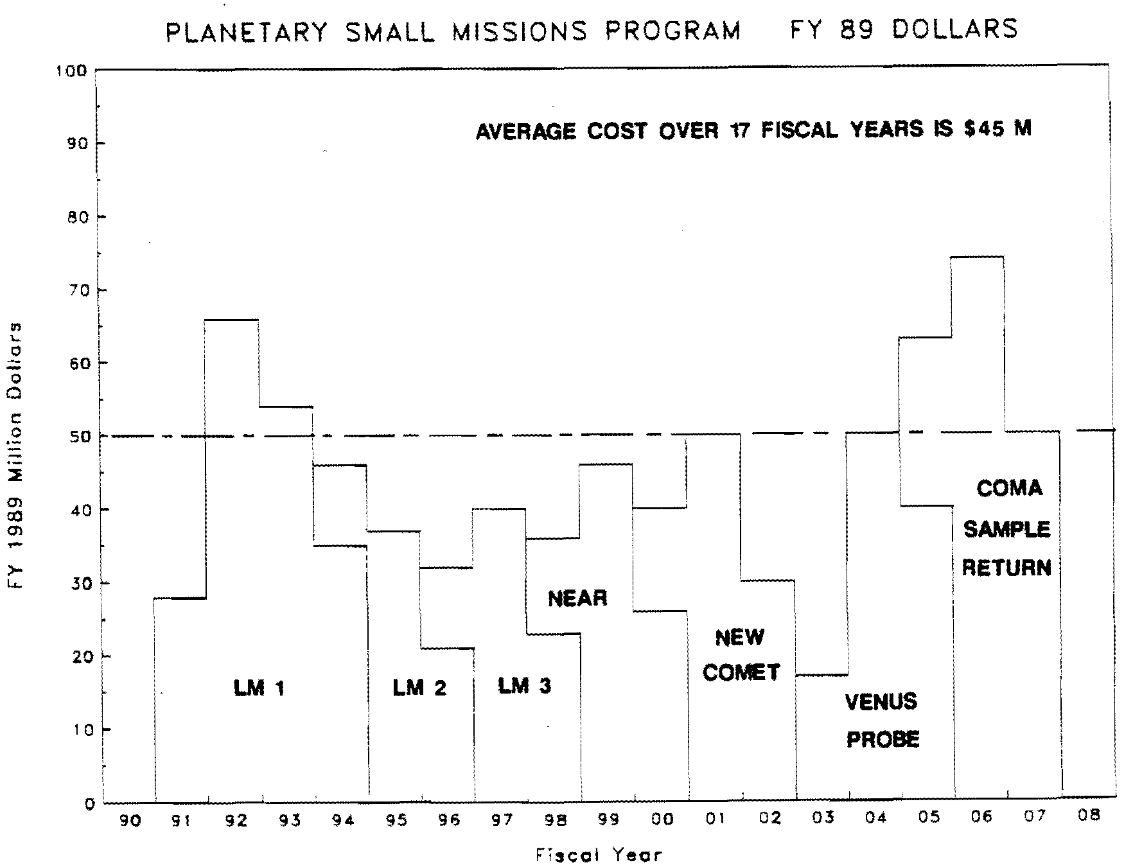


Figure 3: Costing schedule for planetary small missions in FY89 dollars.

available launch vehicles provide either too much or too little capability for the missions proposed. Although the Delta II was selected as the prime launch vehicle, more suitable matches might become available from several manufacturers.

The targets selected for this mission set provide multiple launch opportunities over the lifetime of the program and provide flexibility in program scheduling. A sustainable small missions program, with multiple fallback options, has been developed here for the time period 1994-2010. The program generally meets average annual funding limits of $50 million or less, provided a rolling spare philosophy is maintained, extensive use of previously developed instruments from other programs is made, and block buys of instruments are made whenever possible. More expensive missions can be kept within funding limits by considering international participation or increasing the interval between missions.

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NOTATION

BASD = Ball Aerospace Division
CCSR = Comet Coma Sample Return
CRAF = Comet Rendezvous/Asteroid Flyby
DMSP = Defence Meteorological Satellite Program
DSCS = Defence Satellite Communication System
LM = Lunar Mission
LO = Lunar Observer
MO = Mars Observer
NEAR = Near-Earth Asteroid Rendezvous
PIDDP = Planetary Instrument Design and Development Program
PVLP = Pioneer Venus Large Probe
VIMS = Visual and Infrared Mapping Spectrometer
VAP = Venus Atmospheric Probe
SSI = Solid State Imager