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LOW COST MISSIONS TO EXPLORE THE DIVERSITY OF NEAR EARTH OBJECTS

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ABSTRACT

We propose a series of low-cost flyby missions to perform a *reconnaissance* of near-Earth cometary nuclei and asteroids. The primary scientific goal is to study the physical and chemical *diversity* in these objects. The mission concept is based on the Pegasus launch vehicle. Mission costs, *inclusive* of launch, development, mission operations and analysis, are expected to be near $50M per mission. Launch opportunities occur in all years. The benefits of this reconnaissance to society are stressed.

A RECONNAISSANCE OF NEAR EARTH OBJECTS

In their *Strategy for the Exploration of Primitive Solar-System Bodies - Asteroids, Comets and Meteoroids: 1980-1990* the Committee on Planetary Exploration of the Space Science Board (COMPLEX, 1980) noted that "In order to realize the further goal of understanding the factors that produce diversity in the population of comets, a balanced and economical program of cometary exploration could include flyby as well as rendezvous-mode investigations."

In this paper we propose a series of small, innovative, low-cost flyby missions to make a reconnaissance of near-Earth objects (NEOs) which includes a selection of asteroids as well as cometary nuclei.

NEOs are derived from the main-belt asteroids and periodic comets, and thought to be a collection of collisional fragments, primitive objects, and extinct or dormant cometary nuclei. In addition, many active periodic comets enter near-Earth space and we include them in this population. NEOs are the primary source population of large objects that strike the Earth. The inevitable probability that they have been responsible for cataclysmic impacts on the Earth (Chapman and Morrison, 1989) and the indisputable certainty that these will occur in the future has renewed general interest in these objects to such an extent that the American Institute for Aeronautics and Astronautics (AIAA, 1990) has proposed that they be seriously studied so that ways can be found to protect society from future threats. NEOs also represent the most convenient source of materials needed for future utilization and exploitation of space (Swindle *et al.*, 1991). The interiors of extinct comet nuclei may still be composed of water which makes them important candidates as future base sites for human deep space exploration.

Knowledge of the properties of these objects is sparse (McFadden *et al.*, 1989). Approximately 150 objects are known and about a dozen new objects are discovered each year. The total population is expected to exceed several thousands (Shoemaker *et al.*, 1979). Weissman *et al.* (1989) have surveyed the known population and found that 29 of the objects could be cometary nuclei. Yeomans (1991) finds that the asteroids Icarus and Apollo are possibly nearly-extinct cometary nuclei since their orbital motion appears to be affected by non-gravitational reaction forces.

Low transfer energy (C_3 <5 km^2/sec^2) mission opportunities to these objects are very frequent and small spacecraft with innovative payloads could be delivered to them with short flight times (<1 year) from very low-cost launch vehicles.

Given the combination of wide social interest in these objects with an exceedingly weak scientific understanding of their physical and chemical properties, we propose that the initial reconnaissance of the solar system, so ably undertaken by NASA to the primary planets and satellites of the solar system, *now be extended to NEOs with a series of low-cost flyby missions.*

OTHER REQUIREMENTS

Flagship missions like CRAF, Rosetta, Cassini, Galileo are *absolutely* essential to satisfy the scientific goals of planetary exploration even though they are expensive, complex, and time-consuming endeavors. However, there is also a need for small, low-cost, rapidly completed missions to provide frequent flight opportunities. Flight mission are needed to provide vehicles for the development and testing of innovative instrumentation, mechanisms, communications, systems, and flight software. Opportunities are needed for the training and inspiration of young engineering and scientific talent (Allen, 1990; Coleman, 1990). The United States Senate Appropriations Subcommittee (US, 1991) has recently recognized these problems and has directed NASA to "prepare, with input from the scientific community, a plan to stimulate and develop small planetary or other space science projects...."

In our opinion, the proposed reconnaissance of NEOs will go far to satisfy these demands. Missions could be as frequent as 1-2 per year at all-inclusive costs of roughly $50M per mission. Over the span of an individuals "professional lifetime" there would be the order of 10 to 20 flight opportunities. The total costs of the reconnaissance program, stretched over two decades, would be comparable with the cost of a single flagship mission.

INTERPLANETARY CAPABILITY OF PEGASUS AND COSTS

To constrain total mission costs to around $50M per flight and to provide frequent launch opportunities it is necessary to find a launch vehicle that is in itself inexpensive but has flexible launch characteristics and enough performance and injection accuracy to place small ($\sim$10 kg) instrument payloads on intercept trajectories to a wide selection of NEOs. This requires injection of approximately 100kg with C_3 of 5 km^2/sec^2. The *Pegasus* launch vehicle (Anon, 1989), which was recently selected by NASA and the U.S. Air Force as their "small" launch vehicle (Anon, 1991), meets these requirements. The expected performance is > 85 kg injected mass for C_3 < 5 km^2/sec^2 using a STAR 20A solid rocket motor upper stage (Barnett, 1991). Substantial enhancements of this performance are expected with planned upgrades for the Pegasus series (Schade, 1991), and, in some low C_3 missions, a lunar swingby (Uphoff, 1990) will improve the performance significantly.

The cost of a Pegasus launch (including integration and launch operations) is expected to be about $10M. In Table 1 we show our estimates of the cost and mass apportionments that we expect to be appropriate to small NEO flyby missions.

Table 1: Apportionment of Costs and Mass for a Small NEO Flyby Mission

Mass (kg):		Costs ($M):	
Kick stage adaptors etc.	20	Instrument	10
Spacecraft and systems	40	Spacecraft development	20
Instrument payload	10	Flight Operations	10
		Pegasus launch	10
Total	70kg	Total	$50M

There already exists much experience with small spacecraft designs that fall within these mass and cost constraints and 3-axis stabilized, spinner, and dual-spin configurations are all feasible. In our concept we would expect that the payload would be fully integrated with the spacecraft and provide essential flight functions (terminal guidance, self-sequencing, etc). Communications requirements would be minimized by the use of massive onboard solid-state memory.

MISSION OPPORTUNITIES

In Table 2 we list some low-energy flight opportunities, discovered by Sauer and Yeomans (1990), that occur in the last half of the 1990's and which could be flown by a small spacecraft launched with Pegasus.

Table 2: A Selection of NEO Flyby Opportunities

Object	C_3 (km/sec)^2	Flight time (yrs)	Launch year
Eros	1.892	0.80	1995
Oljato	1.377	0.56	1995
P/Honda-Mrkos-Pad.	3.316	0.72	1995
P/Churyumov-Ger.	4.078	0.67	1995
Dionysius	0.074	0.77	1996
1980 PA	1.272	0.28	1996
Quetzalcoatl	1.549	0.86	1996
Bacchus	1.939	0.78	1996
P/Hartley 2	2.155	1.02	1996
P/Wirtanen	4.000	1.07	1996
1983 RD	1.148	0.86	1997
P/Giacobini-Zinner	1.335	0.97	1997
Geographos	2.018	0.99	1997
1981 ET3	2.333	1.02	1997
Lick	4.481	0.80	1997
Sisyphus	0.752	0.59	1998
McAuliffe	2.287	0.48	1998
Oljato	3.212	0.52	1999

Opportunities of particular interest are Eros (the largest known near-Earth asteroid), Geographos (the most elongated nucleus known), Oljato (possibly a "nearly-extinct" comet), and P/Giacobini-Zinner whose interaction with the solar wind was earlier explored by the International Cometary Explorer (ICE).

All of the above opportunities are to a single object and have short (*i.e.* low-cost) flight missions. Low-energy missions to multiple NEO targets are thought to exist and extended mission scenarios may be possible.

SCIENTIFIC OBJECTIVES AND MEASUREMENT GOALS

To quantify the concept of *diversity*, we have developed a series of scientific questions appropriate to a program of small flyby missions (Table 3). They serve to illustrate the breadth of significant scientific problems that a series of small flyby reconnaissance missions can elucidate:

Table 3: Some High-level Goals for Flyby Missions to near-Earth Objects

Near-Earth Cometary Nuclei:
Do Cometary nuclei, in fact, have diverse physical properties?
Are cometary nuclei chemically inhomogeneous on global scales?
Are major structural differences evident in the surface layers of different comets?
Is the carbon chemistry the same in all comets?
How well can we assess the availability of H_2O on "extinct" or "dormant" comets?
What evolutionary processes are reflected in the appearance of the surfaces of comets?
How does the nature of the interaction with the solar-wind depend on the nature of the comet?
Near-Earth Asteroids:
What evidence is there for collisional formation?
What evidence is there for differentiated objects?
What evidence for post-collisional evolution?
How does the taxonomic classification compare with the physical and chemical properties of their surfaces?

These goals can easily be translated in to a series of measurement objectives (Table 4) appropriate for flyby missions which identifies the kind of payloads that need to be considered:

Table 4: Measurement Goals and Instrument Packages

Surface Composition	Near-Infrared Camera/Spectrometer
Physiographic Units	High-resolution Camera
	Near-Infrared Camera
Global Properties	High-resolution Camera
Surface Morphology	High-resolution Camera
Magnetism and Volatiles	Particles and Fields Package
	Ultra-violet Spectrometer
Dust Composition	Dust Analyzer
Dust Density and Size Distribution	A "smart" Counter
Solar wind Interactions/Coma Aeronomy	Particle and Fields Package
	Ultra-violet Spectrometer

For the proposed reconnaissance a set of about six generic instrument payloads are needed. Many of these instruments already exist, but are too heavy to fly together on a single mission. Micro-technology could reduce instrument size but this path is expensive and, if taken to extremes, could undermine the basic concept of small low-cost missions. We advocate an innovative approach to instrumentation with some miniaturization but maintaining highly focussed measurement goals. In our concept the instrument is merely an extension of the spacecraft itself and would provide many of the functions necessary for supporting the mission. Thus a camera system would provide "lock-on" terminal guidance and might be self-sequencing. We expect that some missions would be focussed entirely on imaging science while others would focus on either aeronomical, particle and fields, or solar-wind interactions.

PROGRAMMATICS

Our experience with previous missions indicates that a four year project cycle should be appropriate. Each mission should be run as a guaranteed design-to-cost project and a short definition phase will be required to ensure that all key areas are clearly defined. The hardware development phase would take approximately 24 months and represents the bulk of the expenditures up to the time of launch. The last phase of the program would be flight operations and data analysis which we estimate would be completed by launch plus 12 months in most cases. This indicates that a reconnaissance program could be supported at an average level of about $25M per year (all-inclusive costs) with a new mission initiated every two years. Current accounting practices in the NASA Solar System Exploration Program separate out the costs for development, launch, and flight operations. The development cost of a series of flyby missions (a new mission start every two years) would average out at about $15M per year to the Solar System Program. This is an unusually low number for flight programs in planetary exploration.

In order to maintain low-costs it is not only necessary to have short missions with highly focussed scientific objectives but experience shows that the development, budgetary, and flight operations responsibilities should be primarily entrusted to a small and dedicated research team. For this reason we advocate that individual missions be carried out by small research groups in university, industrial, or NASA research settings. Overall *program* development, which would encompass the phasing of missions, mission selection, project and budgetary oversight, etc. would be the responsibility of a NASA center. Launch operations would be provided directly by industry.

Finally, on an aggressive note, we believe that expansion of this concept to an international program would foster competition in technical innovation while simultaneously maintaining a healthy cooperation on scientific questions. In many ways the proposed reconnaissance has already begun on the international scene. ICE, flown by the United States to P/Giacobini-Zinner, was the beginning and was closely followed by the Giotto/VEGA/Suisei/Sakigaki flybys to P/Halley. A continuance is certain with the retargeting of the Giotto spacecraft to a future flyby of P/Grigg-Skjellerup and an extension is implicit with already planned future flybys of main-belt asteroids by Galileo (Gaspra and Ida), CRAF (Mandeville), and Cassini (1989 UR1).

BENEFITS TO SOCIETY

The proposed reconnaissance of NEOs offers several benefits to society. It provides frequent access to space for innovative research and experimentation by small university, industry, and government research groups. It therefore provides an enormous increase in the opportunities for young scientists in the formative stage of their careers to participate in the development of space technology and exploration. It helps lay a basis for the utilization of NEOs as space resources in the future human exploration of space. Finally, the scientific exploration of these objects, which at some future time could threaten the earth, will make them familiar to engineers and scientists and better understood by ordinary people who will have to cope with such traumatic events.

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