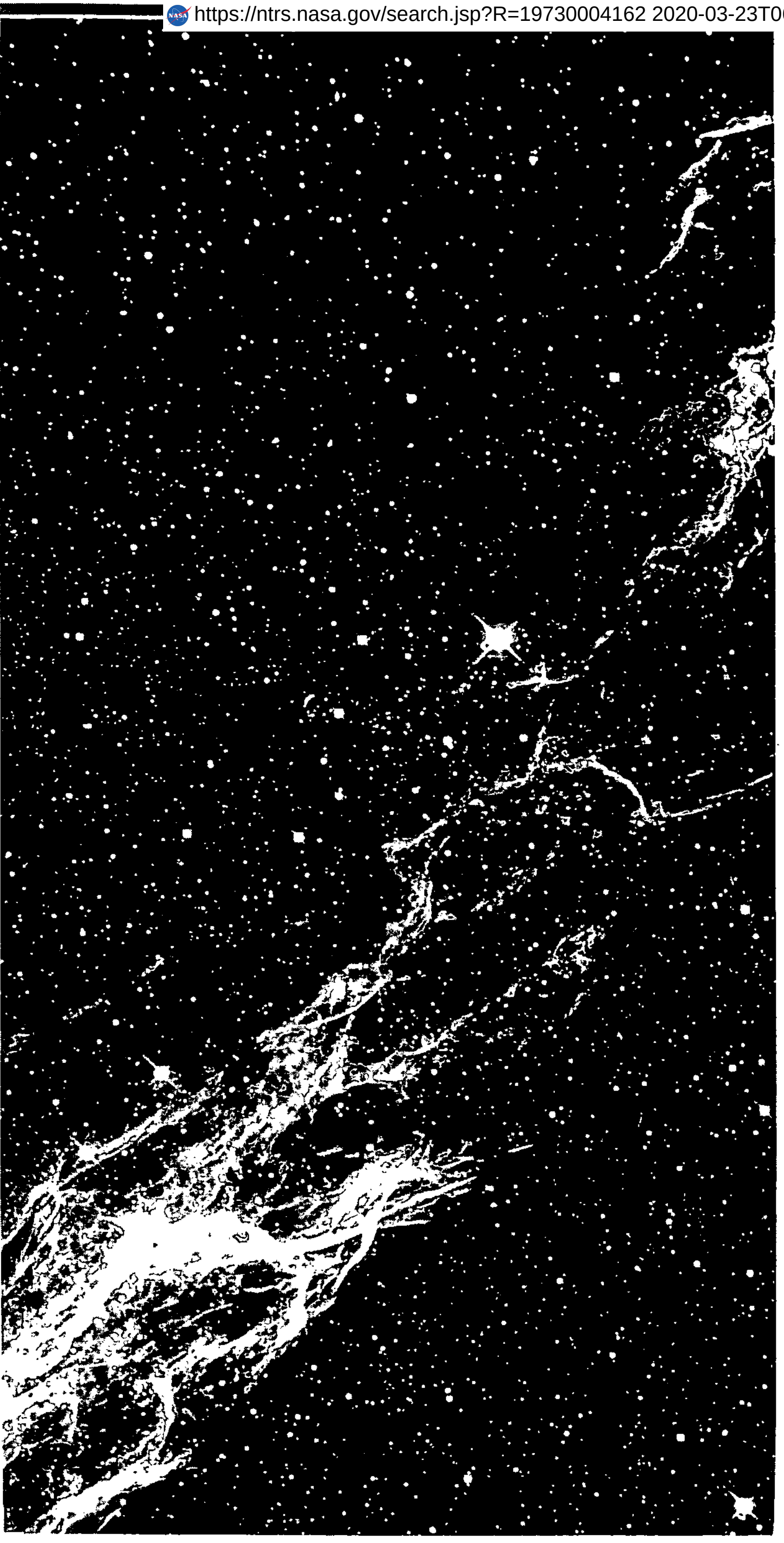
AS

ASTRO SCIENCES



Technical Memorandum P-42

ASTEROID SELECTION FOR MISSION OPPORTUNITIES

IIT RESEARCH

10 West 35 Str

Chicago,

Technical Memorandum No. P-42

ASTEROID SELECTION FOR MISSION OPPORTUNITIES

by

C. R. Chapman
and
C. A. Stone

Astro Sciences
IIT Research Institute
Chicago, Illinois 60616

for

Planetary Programs
Office of Space Sciences
NASA Headquarters
Washington, D. C.

Contract No. NASW-2144

APPROVED BY:

C. A. Stone, Director
Physics Research Division
IIT RESEARCH INSTITUTE

November 1972

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

REFERENCES

Brooks, D. R., Drewry, J. W. and Hampshire, W. F., 1972, "Multiple Asteroid Flyby Opportunities in the 1970's and 1980's", AIAA Paper No. 72-52.

Chapman, C. R., 1971, "Surface Properties of Asteroids", Ph.D. Thesis, Massachusetts Institute of Technology.

Gehrels, T., 1970, Photometry of Asteroids in "Surfaces and Interiors of Planets and Satellites", (A. Dollfus, ed.), Academic Press, London, 317-375.

Lacis, A. and Fix, J., 1971, Light-Curve Inversion and Reflectivity in "Physical Studies of Minor Planets", (T. Gehrels, ed.), NASA SP-267.

Matson, D. L., 1971, Infrared Observations of Asteroids in "Physical Studies of Minor Planets", (T. Gehrels, ed.), NASA SP-267.

Taylor, R. C., 1971, Photometric Observations and Reductions of Light-Curves of Asteroids in "Physical Studies of Minor Planets", (T. Gehrels, ed.), NASA SP-267.

Van Houten, C. J., van Houten-Groeneveld, I., Herget, P. and Gehrels, T., 1970, The Palomar-Leiden Survey of Faint Minor Planets, Astron. Astrophys. Suppl. Ser. 2, 339-448.

Vesely, C., 1971, Summary on Orientations of Rotation Axes in "Physical Studies of Minor Planets", (T. Gehrels, ed.), NASA SP-267.

Veverka, J. F., 1970, "Photometric Studies of Minor Planets and Satellites", Ph.D. Dissertation, Harvard University.

ASTEROID SELECTION FOR MISSION OPPORTUNITIES

1. INTRODUCTION

Missions to the asteroid belt and to specific asteroids were identified as scientifically important very early in the space program and flyby opportunities to one or more of the larger asteroids have appeared in NASA long range plans for a number of years. These opportunities have largely been selected on the basis of launch opportunity and mission energy requirements. More recently it has become apparent through rapid advances in our limited knowledge of the asteroids that the major questions which relate to solar system minor bodies will not be satisfactorily answered, even in the first order, by a mission or missions to a single asteroid. Concurrently, advanced propulsion systems are being developed or planned which expand the mission possibilities for minor bodies. Solar electric propulsion (SEP) and nuclear electric systems (NEP), when available, are capable of performing rendezvous and orbit, multiple asteroid flybys, and lander missions.

This preliminary study was undertaken to assess the present state of knowledge of asteroids as well as the rate of change of that knowledge to better identify the mission and target priorities for the advanced planning of asteroidal flights in the 1980's and beyond. It was apparent at the outset that there was not a unique set of asteroids representing maximum priority. Equally important, ground based observations and studies will undoubtedly alter priorities assigned to specific asteroids as our knowledge increases. Thus this report presents a review of current knowledge and derives a categorical set of priorities which can be applied to asteroid selection or evaluation by the reader. A preliminary selection has been made both to illustrate the process and to provide the basis for early mission analysis but this selection should not be construed as representing the only choice nor even the "best" one.

The report discusses, in order, the present state of asteroid knowledge, the scientific goals and priorities attached to asteroid exploration, the anticipated advances in knowledge over the current decade, asteroid mission consideration and, finally, asteroid selection. Data sheets for 118 asteroids are contained in an appendix. These are asteroids for which some data is available over and above orbital parameters and magnitude. Continued updating of these data sheets together with the selection framework provided herein should provide mission planners with the necessary material to make target selections for study or to evaluate selections which have been derived from trajectory considerations.

2. PRESENT STATE OF ASTEROID KNOWLEDGE

The asteroids are a large collection of bodies, generally located in orbits between those of Mars and Jupiter, ranging in diameter from about 1000 km downwards to mere boulders in space. Rather little is known about asteroids, but they clearly constitute an important source of information relating to the early evolution of the solar system and subsequent evolutionary processes. Because of the small sizes of asteroids, many kinds of studies which have been made of the planets cannot be applied to asteroids. Thus, they are particularly amenable to close-up study by spacecraft. On the other hand, planning for such missions is complicated by two factors: (1) far less is known about the asteroids today than has been known at an equivalent time in planning of missions to the planets; (2) the importance of the asteroids lies primarily in the comparative studies of an ensemble of bodies in widely differing orbits rather than in detailed studies of one or a few individual asteroids unrelated to the others -- a consideration obviously at variance to the generally assumed mission constraint of visiting, at most, a few asteroids.

2.1 Growth of Knowledge About Asteroids

Asteroids were first discovered over a century and a half ago. For the first century, all work on asteroids related to their discovery and calculation of precise orbits for them. This activity remained predominant until very recently and continues today. However, during the twentieth century there have been increasing attempts to study the physical properties of asteroids, as well as to study dynamical, collisional, and chemical processes in the asteroid belt.

The rate of these studies has increased remarkably in the last few years. The field is clearly on the threshold of a great leap forward (given sufficient support), not only with regard to collecting diverse kinds of data about a much larger sample of asteroids, but also with regard to organization, synthesis, and interpretation of such data. The I.A.U. Colloquim on the Physical Properties of Minor Planets, held in Tucson in the spring of 1971, provided a focus for these new studies and they are progressing at a great rate. Several new methods of studying asteroids have recently been developed (thermal IR measurements of asteroid diameters and albedoes; measurement of mineral absorption bands in the near IR; etc.). The first major revision and analysis of asteroidal proper orbital elements is just now being completed by Williams. The Palomar-Leiden Survey (Houten, et al, 1970) is the first major extension of asteroidal statistics to fainter magnitudes since the Kuiper survey of the mid-1950's. Gehrels has recently revised the photometric characteristics of all known asteroids. Alfven, Arrhenius, and their colleagues have introduced the most radically new concept for accreting asteroids (involving jet streams) advanced in many years, spurring work by others. Major advances have also been made recently, in part by the use of high-speed computer calculations, at determining whether or not meteorites originate in the asteroid belt. If current work is successful in connecting the origins of certain classes of meteorites to certain particular asteroids, or asteroid families, then a wide body of meteoritical data will suddenly become applicable to the asteroids. As a final spur to these studies, a new 70-inch telescope is now being built for the chief purpose of observing asteroids.

It is important to bear in mind the exponential increase in knowledge about these bodies which is taking place right now. These is every reason to believe that what is known today, and the research problems currently of greatest interest, will have long since been surpassed by the time of the first asteroid space mission. Thus, in many ways, the selection of appropriate asteroid targets in this report must be regarded as only exemplifying the process of selecting appropriate targets. The targets of priority will almost certainly be different a decade hence even if some or all of the scientific goals survive.

2.2 Ground-Based Methods for Studying Asteroids

Position measurements. (Astrometry). Venerable astronomical techniques for measuring positions of asteroids continue to be used for orbit determination. By utilizing orbit theory, it is possible to derive the proper orbital elements which are those elements with oscillating components (due to perturbations) removed. From the statistical ensemble of these orbits (nearly 1800 are listed in the current ephemeris), we learn about Hirayama families, possible jet streams, the Kirkwood gaps, and other distributional characteristics. Collision and perturbation probabilities can also be computed. Mutual perturbations by asteroids permit determination of asteroidal masses; the technique has so far been applied to two asteroids, and is believed not to be readily applicable to others.

Photometry. Approximate magnitudes are known for nearly all asteroids with computed orbits. Some of these are quite poorly determined whereas many others are precise. Gehrels (1970) presents the most up-to-date compilation of asteroid magnitudes (the B magnitude on the UBV photometric scale.) The variation of asteroid brightness as a function of phase angle, which is related to surface texture, has been determined for about two dozen asteroids. Perhaps the major photometric behavior of interest is the light-curves -- the variation in brightness of an asteroid as it spins on its axis, due to non-spherical shape and/or surface spottedness. Light-curves have been observed for about 60 asteroids, mainly by Kuiper, Gehrels, and their co-workers, and by the Changs; the results for most have been summarized by Taylor (1971). Most asteroid light-curves have yielded unambiguous rotation periods, although a few have either a factor of two ambiguity or no variation at all. It is possible in part to sort out the effects due to shape and spottedness, but only qualitative comparisons have been made to date. In principle, through many observations, the rotation axis can be determined uniquely from the light-curve;

such calculations have been performed for 16 asteroids, but the results are believed secure for few of them (Vesely, 1971).

Spectrophotometry. The colors (or spectral reflectivities) of asteroids provide information on their surface composition, both mineralogical and textural. The various techniques applied over the years (photographic colorimetry, UBV and other photoelectric photometry, and filter spectrophotometry) have been re-examined by Chapman (1971) and he finds reliable approximate colors for 102 asteroids. Of these, 32 have had their spectral reflectivity completely defined by filter spectrophotometry throughout the visible and near-IR. Fourteen additional asteroids have been successfully observed using these techniques by Chapman and his associates, but the data are not yet reduced. Absorption bands, which provide diagnostic clues to the mineralogy have been found for about half of the 32 so far measured. As with photometry, one may search for variations in color changes with rotation which have been positively detected for two asteroids, and suspected for several more. At least one asteroid has been detected in the IR near two microns, but detailed reflectivity measurements at these wavelengths have not yet been made.

Polarimetry. The measurement of polarization of light reflected from asteroid surfaces, especially as a function of phase angle, yields important information about the physical properties of the surface (e.g. texture and albedo). The polarization-phase relation has been measured for less than a dozen asteroids, chiefly by Veverka (1970).

Infrared Photometry of Thermal Emission. Measurements of thermal flux emitted by asteroids in the 8-12 micron window provide estimates of the Bond albedos and diameters of asteroids, and in principle some information about the thermal properties of the materials of which asteroids are composed. Matson (1971) has studied 26 asteroids in this manner and has obtained good data for 16 of them.

Radar. The reflection of radar from asteroids is a technique still in its infancy, having been applied only to Icarus and Toro. In principle, one can measure the spin axis and period, the diameter, and the radar reflectivity (related to dielectric constant and surface porosity), and the scattering function and polarizing properties which, among other things, are related to surface roughness at radar wavelengths. More detailed techniques, already applied to some planets, are well beyond the state-of-the-art for asteroids. The technique is most readily applicable to Apollo asteroids which pass very near the earth. Among main belt asteroids, only the very largest of them (especially those with small perihelia) appear to be marginally detectable today, although attempts to detect them have not yet been made.

Direct Diameter Measurements. There have been micrometric and interferometric measurements of the diameters of four large asteroids, but the errors are probably at least 30 percent and there seems to be little future utility for such techniques. Occultations of stars by asteroids commonly occur and can yield very accurate diameter estimates. Accurate predictions and considerable logistical effort is required to observe such events. Although two stellar occultations by asteroids have been observed, two chords (necessary to determine a diameter) were not obtained.

2.3 Properties of Asteroids

A fair amount of what we believe we know or can hypothesize about the asteroids is derived from largely theoretical studies, including: physics of deformation of large bodies, orbital dynamical studies, early solar system models and related chemical and physical investigations, studies of collisions and fragmentation, etc. To the extent that meteorites may originate in the asteroid belt, the rapidly increasing amount of physical, mineralogical, and petrological data on meteorites may apply to the asteroids. Several meteorite parent-body models have been derived which can be regarded as asteroid models.

Little is known about most asteroids. In general, they are a highly variegated sample of bodies with respect to most of the observable characteristics. However, we can be reasonably confident of our knowledge of many properties of at least a few asteroids. The densities of the two measured asteroids are low (around 2 g/cm^3); Vesta may be denser than Ceres, but it is not certain. The diameters of asteroids range downwards from about 1000 km (Ceres) to small meteoroids; a discontinuity in the size-frequency relation near 60 km diameter may reflect the boundary between the population of original condensations and subsequent fragments. Asteroids are approximately spherical in shape, with some irregularities. Elongated objects with major axes in excess of twice the length of the least axes are quite unusual, and are confined to the smaller sizes. The widely distributed Mariner 9 photographs of Phobos and Deimos illustrate typical asteroidal shapes.

Rotation periods for asteroids are in the range of two to twenty hours with most lying in the range five to twelve hours; there is no obvious correlation of rotation period with size. There are some indications for a preponderance of high axial obliquities, but the data are uncertain. Although shapes contribute predominantly to asteroid light curves, there is an appreciable component due to surface albedo differences. None are so extreme as the Saturn satellite Iapetus, however. Color differences as a function of rotation are also comparatively small, but they have been noticed for Vesta and Hebe.

Asteroid albedoes are similar to or darker than the moon, with Bond[1] albedoes spanning the range one percent to twelve percent. Negative branches of the polarization-phase curves and some other photometric properties indicate that asteroid surfaces are porous or dusty although theoretical analysis (Chapman, 1971) suggests that regoliths should not develop on very small asteroids.

Asteroid colors range from being nearly as "red" as the moon to being slightly "bluer" than the sun. The visible and near-IR spectral reflectivity curves are of many different types. Of 32 observed asteroids, there are at least 14 significantly distinct curve types. About half of the asteroids show weak infrared absorption bands, probably indicative of pigeonites, hypersthenes, and olivines. The remaining reflectivity curves bear strong resemblances to basalts, carbonaceous chondrites, and other assemblages of opaques. The implied surface compositions seem to resemble the ensemble of meteorite mineralogies.

The distribution of asteroidal orbits indicate strong influence by both Mars and Jupiter in perturbing and capturing asteroids. The groupings of asteroids in "a-e-i space", known as Hirayama families, are especially interesting due to the possibility that they are the remnants of asteroidal collisions. Although a number of characteristics of such families have been determined (size-frequency relation, distribution of colors, location of the primary member with respect to the center of the family in a-e-i space, etc.), such work must largely be redone because the orbit theory previously used for deriving proper orbital elements has been inexact. Williams has been calculating new and much better proper elements. Although the existence of jet streams (clusterings among five asteroidal orbital elements) has been proposed and has significant

[1] Bond albedo = geometric albedo times the phase integral.

implications for dynamical and accretionary processes in the belt, the reality of such streams has been questioned in the light of selection biases. Much attention has been devoted to synamical mechanisms for obtaining meteorites from the asteroid belt. In general it is difficult to do; however, Anders has suggested ways of getting meteorites from the Mars-crossing or nearly-Mars crossing asteroids, while Zimmerman and Wetherill have devised a possible mechanism for deriving meteorites from asteroidal fragments originating near the 2:1 resonance with Jupiter. There appears to be no necessity as yet to search for non-asteroidal sources for all meteorites.

Correlations between many asteroidal parameters (orbital and physical) have been found, such as a correlation of size and color, color and semi-major axis, light-curve amplitude and size, and mean inclination and semi-major axis. The degree to which some of these correlations may reflect biased statistics has not been fully examined, nor are the physical implications clear.

2.4 Origin and Evolution of the Asteroids

The physical data which have recently been collected about some asteroids have not been available long enough to become thoroughly assimilated into models for the origin and evolutionary processes in the asteroid belt. A number of models have been constructed -- both meteorite parent body models and asteroid collisional and fragmentation models -- but there seems to be little confidence that these models are complete, even on the part of their proponents.

Most hypotheses for the origin of the asteroids have been shaped in part by historical peculiarities, heavily modified by geochemical and petrological studies of meteorites which have long been presumed to be asteroidal fragments. Thus, Bode's Law led to the prediction of a planet at 2.8 AU and searches for it were underway when Ceres was accidentally discovered. Ceres proved to be very small, but when three additional asteroids were soon discovered at the same solar distance, the concept of an "exploded planet" became widely accepted. The contrary hypothesis of a planet which never formed took longer to develop.

It is now widely believed, although not proven beyond doubt, that there never was sufficient material in the region of the asteroid belt to produce a planet. It is difficult to remove asteroidal fragments in such quantities as to leave the small amount of mass currently existing in the belt (estimated at several times Ceres mass). Moreover, analyses of meteorite parent bodies which a decade ago were believed to be lunar size or bigger, but are now thought to be more nearly asteroidal in size.

In broad outline, the asteroids can be thought of as remnants of the early processes of condensation and accretion in the early solar nebula which eventually led to the growth of planets. For reasons not yet fully understood, but presumed by many to be due to perturbation effects of nearby Jupiter, the volume density of grains, planetesimals, etc. was too low in the vicinity of the asteroid belt to permit accretion to proceed to the development of a single planet. However, the process went partway -- to the planetesimal stage -- and the present day asteroids are remnant planetesimals dating from early stage of solar system evolution. There have been continuing and competing processes of accretion and fragmentation which have modified the physical state (e.g. size distribution, shapes, regoliths, etc.) of the asteroids, but the minerological and geochemical characteristics of asteroids have been largely unchanged since their formation.

The specific compositions of asteroids reflect the processes of condensation and chemical interaction which occurred in different ways in different parts of the solar system, depending upon the temperature/pressure relations in the solar nebula as a function of position and time. Subsequent to formation, the larger planetesimals or asteroids were probably not exclusively due to gravitational energy). This produced metallic cores and basaltic surfaces. However, there are other interpretations from meteoritics which do not derive all meteorites from the asteroid belt and there are dynamical problems with getting asteroidal fragments from the main belt to earth. If meteorites do not come from the asteroid belt, then we know far less about the origin of asteroids than we had thought.

3. SCIENTIFIC GOALS AND PRIORITIES

If we are to intelligently select a list of high-priority asteroid targets for space missions, we must first identify the scientific questions of most fundamental importance. This is a difficult task in the philosophical sense, but we can readily identify certain broad questions which seem particularly exciting and seem to have the largest implications for our conception of the solar system.

3.1 Origin of the Solar System

The asteroids may be the Rosetta Stones of the solar system. As already discussed, there are indications that the asteroid belt is a region of the solar system where the processes of condensation and accretion, which led to the formation of planets, never went to completion. In some ways, then, the asteroid belt may present a tableaux of an early stage of solar system history. Perhaps more fundamentally, the asteroids are sufficiently small that they may be composed of rocks and other materials not substantially modified since the time they were formed aeons ago. The asteroids are sufficiently small that few of them have been substantially affected by processes of melting and metamorphism to which rocks in larger and hotter planets have been subjected. The creation of great atmospheres and oceans, which has taken place on most planets, and the outpourings of great sheets of lava which have occurred during an appreciable part of the lifetime of even such a small body as the moon and which serve to erase early history, must have been largely absent on asteroids. Even the great thicknesses of ejecta blankets and the thinner regolith mixtures, encountered by astronauts on the moon, should be even thinner and less difficult to penetrate on asteroids.

The most fundamental and helpful question we can address, in the hopes of solving the solar system origin problem is the relationship of meteorites (which have been so extensively studied) to the asteroids. Present indications are that meteorites come from a small number of "parent bodies". If these parent bodies can be identified with individual asteroids or -- more likely -- asteroid families, then we can tie down the numerous meteoritical results concerning condensation sequences, cooling times, etc., to specific parts of the solar system. Some meteoritical hypotheses derive chondrites from small bodies, and achondrites, pallasites, and other differentiated meteorites from larger ones. It is therefore, important to determine which asteroids may have differentiated.

It has been suggested by Whipple that the whole goal of asteroidal exploration should be aimed towards solving the "Grand Canyon problem". He suggests the analogy of giving to geologists rocks collected from every stratum of the Grand Canyon, but then jumbled up so that there is no stratigraphic information concerning their relative locations and orientations. From such evidence, it would be monumentally difficult to piece together a coherent chronology for the geological evolution of the Grand Canyon. Meteorites are similar kinds of rock fragments, with little specific evidence as to their spatial and temporal positions during such a framework for meteorites by further study of the asteroids.

The early dynamical evolution of the asteroids is another matter of considerable importance. It is presumed that during the earliest stages of solar system history asteroid precursors had more circular and similar orbits. Otherwise their relative speeds would have been too high to permit accretion, and net fragmentation and dispersal would have resulted. However, in intervening epochs the orbits have become dispersed to the extent that mean collision velocities are about 5 km/sec.

Gaps have been produced in the volume density of the asteroids as a function of semi-major axis, probably due to perturbations or removal of asteroids having orbital commensurabilities with other objects, chiefly Jupiter. Whatever asteroids may have existed inwards of the present-day inner boundary of the main belt have been almost totally removed by encounters with, or deflections by, Mars. The role of asteroids in cratering Mars, the moon, and other objects is of considerable interest and there has been some progress made towards calculating collision probabilities of present day asteroids with such planets and satellites. However, there is as yet little understanding about possibilities that there were earlier populations of asteroids -- now totally depleted -- which had much shorter lifetimes against collision and which might have been far more important in earlier cratering.

An understanding of the dynamical evolution of the asteroids, at least since they were formed, has a feedback implication for understanding the "Grand Canyon problem". We will want to measure numerous petrological, mineralogical, chemical, and physical properties of asteroids with the aim of tying down the various processes and environments with respect to location in the early solar nebula (distance from the sun and distance above the ecliptic plane). The asteroids are now certainly dispersed from their original orbits, but dynamical studies can tell us just how skewed the present distribution is and perhaps can tell us which asteroids came from what original orbit.

The early solar system was characterized by rapid and complex changes. As temperatures and pressures fell, more and more compounds condensed out and began slowly to accrete. Chemical reactions were taking place, the solar wind was sweeping materials away at variable rates, magnetic fields were affecting the motions and behavior of magnetic particles, nucleosynthesis was continuing in the sun, certain short-lived radioisotopes were giving rise to local heating in bodies in which they became concentrated, hydrodynamic processes gradually gave way to Keplerian dynamics, and so on. Throughout this history, asteroids and planetesimals were growing by accretion, and in the course of their revolution in increasingly elliptical and inclined orbits, they passed through a suite of environments where these processes were occuring at different rates and in different ways. Thus, the minerals that were built up layer upon layer presumably retain the information diagnostic of the conditions under which they crystallized. Meanwhile, the larger asteroids began to get hot, perhaps by heating by the solar wind or perhaps by short-lived radio nuclides. In any case they began to chemically differentiate.

This entire sequence can perhaps be determined, at least for the region of the solar system between 1 and 5 AU, by detailed measurements of asteroidal rocks. The parameters one wishes to vary include asteroid size, semi-major axis, inclination, depth within the asteroid or asteroid precursor, and others. Such simple characterization of asteroid surface mineralogy as is obtained by ground-based spectrophotometry of near-IR absorption bands is clearly just the first step in the process of unravelling this complicated sequence. A complete analysis of asteroidal rocks, in the manner of analysis of returned lunar samples, is the ultimate step (including age-dating, exposure ages, magnetization measurements, trace element analysis, and so on).

It is here that meteoritics plays such a potentially large role. We can never hope to analyze rocks from more than a few asteroids in the forseeable future -- far too few to permit reconstruction of the entire sequence. We must hope that our sampling through collection of meteorites is sufficiently far-ranging so as not to necessitate visiting an unrealistic number of asteroids. We should be aiming, therefore, to visit those asteroids which will permit calibration of the results of meteoritics to a few particularly important and different asteroids and to make those studies which will most reliably permit us to locate meteorite parent bodies unambiguously.

3.2 Solar System Processes

Philosophically, we are perhaps just as interested in how the solar system is evolving -- how it works -- as we are in how it all got started. Certainly, the most complicated evolution is taking place on and within the planets, excluding the fundamental but conceptually simpler evolution of the sun itself. There are several kinds of evolutionary processes to which the small-body population of the solar system is subject which are also of fundamental interest. These include the dynamical evolution of the solar system, accretion/fragmentation processes and the development of regoliths, and the formation and decay of comets.

The dynamical evolution relates to such processes as the development of resonances with the planets, the capture of asteroids into planetary satellite systems, the ejection of bodies from the solar system, the sweeping up of small bodies by collisions with the major planets, the conversion of asteroidal orbits into earth-crossing orbits, etc. The overall dynamical stability of the solar system is of great interest. To what degree can we regard the current distribution of objects as representative of the distant past? To what degree must we rely on non-gravitational processes to explain observed orbital characteristics? Can we account for saturated crater fields on the moon and Mars by asteroidal objects of some type or can they only be viewed as the end result of the accretion processes which formed those bodies? Despite the fundamental importance of these questions, however, most information about dynamical processes must be indirect or computationally derived. There are no observables which translate directly into orbital parameters as a function of time.

The accretion/fragmentation processes and development of regoliths, are processes more amenable to observational investigation. There is a population of particles distributed throughout the solar system, most densely in the asteroid belt, of which the asteroids are the largest objects but extending downwards to sub-micron dust. These objects and particles are continually colliding with each other. Some particles stick together, but most impact with sufficient velocity that the particles are fragmented and a spray of chips is ejected from the surface of the larger body. This process produces a shattered layer of rubble on larger bodies called a regolith and also is the dominant source mechanism for smaller particles in the solar system, which need to be continually replenished as the Poynting-Robertson effect and other processes remove them.

At some point in solar system history, there was a net sticking of small particles ---- accretion. Yet today the observed distribution of orbits indicates that even bodies as large as the moon are losing more particles to space than they are gaining. It is important to characterize these processes as accurately as possible. This includes determining the mass-frequency relation for particles, as a function of position and orbit; definition of asteroidal cratering processes, at all size ranges, including velocity and angle distributions for spray ejected from impacts with materials of asteroidal composition; determining the behavior of fragments when two large asteroids collide; determining the efficiency of all processes which serve to remove dust from the belt; measuring deviations in mean orbital parameters as a function of body size; and investigating dynamical processes which may tend to cause net accretion, such as the jet streaming proposed by Alfven.

Of particular interest are the Hirayama families of asteroids. If, as many workers believe, the members of a family are the fragmentation products of catastrophic collision then we can piece together details of the collision and reconstruct the original bodies. The size distribution and shapes of family members will provide important clues to the nature of catastrophic collision. Another important test is whether or not rotation periods of family members indicate equipartition of rotational kinetic energy.

Another continuing solar system process is the continuing loss of volatiles to space. The stability field for ice over the age of the solar system may be in the outer parts of the asteroid belt; investigating whether or not this is true (and whether or not the Galilean satellites are icy) is important. Perhaps the most obvious phenomena relating to loss of volatiles are comets. There have been suggestions that some asteroids, because of their shapes and orbital characteristics, may be dead comets. It is particularly critical to establish the boundary between the population of asteroids and that of comets, if one exists, or to study closely the evolution of comets into asteroids if that occurs.

3.3 The Asteroid Belt as a Planet

The temptation is great to think of the asteroids as a collection of little worlds and to think of target selection as the task of determining which of these are most interesting. This is a fallacious approach, however. While many asteroids may be inherently interesting --- some more than others --- the fundamental thing of interest is the asteroid belt as a whole. The relationships between asteroids are far more important than absolute measurements of individual asteroids. What are the relationships between the members of a Hirayama family? How does the mineralogy vary as a function of distance from the sun? As a function of asteroid size? How do asteroidal regoliths vary in thickness as a function of size, mean relative impact velocity, etc? These kinds of comparisons mostly directly help answer the questions posed earlier. Certainly we already have asteroidal fragments in our museum meteorite collections which have been extensively measured in terms of absolute numbers. What we lack are comparisons, spatial/temporal relationships, and relationships between groups (Hirayama families, Apollo asteroids, comets, etc.).

It is useful to think of the task as analogous to that of target selection for lunar sites, or for sites on even more complex planets than the moon. While much was learned from the returned samples from Tranquillity Base (from which we did not previously have samples, in meteorite collections or anywhere), probably the greatest strides in understanding the moon have come from comparisons of rocks and site geology at different locations on the moon. We have sampled maria of different ages, highlands, the Fra Mauro formation, and highland/maria interfaces. The comparisons have often been surprising and revealing. Similarly, an extraterrestrial visitor to earth could make sense of our complex planet only by comparing cities, deserts, mountain ranges, mid-ocean ridges, tundra, volcanic fields, etc. Although the asteroid belt is not, in fact, a broken up planet with sites currently distributed in orbit about the sun, it is nevertheless, useful to think of it that way. Thus, one should think of the entire asteroid belt as a planet and attempt to select appropriate targets for piecing together the origin and evolution of the entire ensemble. Many asteroids probably are fragments of pre-existing larger bodies, but even those that are not were formed at similar times in a spectrum of environments. Their variable positions in a critical part of the solar system, and their variable sizes in a critical sub-planetary size range, provide a high potential for meaningful comparisons.

Practical considerations will limit the number of minor planets that can be visited in the forseeable future. Hence, we should aim to target those which will span the range of the most important variables, and permit ground-based techniques to be calibrated so that useful interpolations can be made to those that cannot actually be visited.

4. ANTICIPATED ADVANCES IN ASTEROID KNOWLEDGE

As mentioned earlier, knowledge about asteroids is increasing at a very rapid rate. Compared with what we know today, practically nothing was known a few years or a decade ago. Before final target selection will be necessary, both observational data and theoretical understanding of asteroids will have improved again by a similar degree. While one cannot forecast specific advances, the additional information which probably will be obtained in the next decade can be qualitatively discussed.

4.1 Observational Programs

Asteroids will continue to be discovered during the 1970's. It is certainly now technically feasible to discover and compute orbits for many times the number of asteroids for which orbits now exist. Many new ones, in fact, were detected in the Palomar-Leiden Survey (PLS). Some hundreds of additional asteroids may be cataloged and future survey programs may be carried out to refine the statistical characteristics of the asteroid belt beyond that accomplished by the PLS. Future efforts at asteroid discovery will probably concentrate on a few especially important kinds of asteroids. At least two programs are being initiated to discover Apollo asteroids and there will be increased efforts to find Trojans associated with Saturn. Unfortunately, lack of manpower will undoubtedly restrict the numbers of asteroids for which reliable orbits can be determined. Asteroid orbits are sufficiently well known to be used in statistical studies and for finding asteroids in the sky. But they are almost all inadequate for use in mission execution. The difficult task of improving asteroid orbits will probably await preliminary target selection.

With adequate funding, there is sufficient interest to insure that photometric, spectrophotometric, and polarimetric measurements will be made on a wide scale. Whereas to date only a few dozen asteroids have had their light-curves, spectra, and phase-dependent photometric properties determined, it is possible that several hundred can be measured over the next several years. Measurements of thermal flux from asteroids can proceed at nearly the same rate. Predictions for the future utilization of radar on asteroids is especially dependent on the availability of improved radar components; nevertheless, it seems likely that at least a dozen asteroids can be measured by this technique in the near future (chiefly Apollo objects and the largest asteroids in the main belt).

Not only will the kinds of measurements be extended from a few asteroids to many asteroids, but the precision of the data will be imporved. One can expect photometric calibrations to be improved to the extent that systematic errors need not exceed one half percent, guaranteeing one percent photometry. When combined with better spectral resolution and quantum efficiency, these developments should permit the measurement of the centers of several-percent absorption bands to a resolution of 0.0005 microns. The development of a vidicon tube with extremely efficient detectors, such as gallium arsenide, is forseeable. Used as a spectrometer, such a device will improve operating efficiencies by two orders of magnitude. It will soon be possible to obtain good spectra of some asteroids in the 1.1 to 2.5 micron region where there are many diagnostic absorption bands. Efficiencies and calibration of thermal radiometry are also rapidly improving.

The availability of telescope time, manpower, and efficient equipment should also produce substantially more complete photometric observations which will permit data-reduction methods to be used that have not been possible before.

For instance, the technique of "photometric astrometry" --- determining the shapes of asteroids and orientations of their poles of rotation --- has only barely been tested because of insufficient data. We can expect good pole determinations for several dozen asteroids in the next decade. New techniques for studying asteroids will certainly be devised, as well. One promising technique, which has not yet been utilized, is the measurement of asteroid diameters by stellar occultations (Chapman, 1971).

The new observational data will permit more highly developed interpretations and comparisons than has been possible before. We will have data for dozens to hundreds of asteroids of the following kinds: diameter; shape; polar orientation; rotation period; orbital elements; family membership; spectrum (0.3 - 2.5 microns, $\Delta\lambda$ = 0.1 micron); some indication of albedo and color variations with rotation; phase variations of brightness, color, and polarization; and probably some information on roughness at radar wavelengths, dielectric constant, and thermal properties of surface materials. Certainly intercomparisons of these parameters will yield important correlations and lead to greater insight about relationships between asteroids. Detailed interpretations will yield more refined mineralogical identifications than has been possible to date and probably some meaningful understanding of asteroid regolith properties. We also may expect the approximate relationship of Hirayama family members to each other will be sorted out (i.e. whether or not they can be fragments from a single catastrophic collision).

Progress in related areas will certainly assist our understanding of asteroids. The optical properties of rocks and meteorites will be investigated heavily during coming years and a complete understanding of the physical origin for spectral reflectance albedo curves, as a function of mineralogy, grain size, and viewing and illumination geometries should be achieved, at least to the accuracy necessary for interpreting asteroid data. The degree to which such measurements can be uniquely diagnostic will still be debated, but opinions will have converged considerably. Analysis of meteorites and lunar samples will continue to develop our understanding of phenomena related to asteroids.

4.2 Theoretical Advances

Theoretical advances are the hardest to predict. Still it is safe to assume that orbital dynamical calculations will have gone a long way toward answering such fundamental questions as whether or not the jet streaming process of accretion is a real and important process and whether or not it is dynamically possible to derive meteorites from the main asteroid belt. It is likely that there will still be divergent views about the early evolution of the solar nebula, but physical and chemical models now emerging will have been considerably refined and will be open to clear observational tests. There will also be continuing refinements to the characteristics of meteorite parent bodies derived from meteoritical studies.

There will soon be considerably better understanding of regolith development processes on asteroids. Today there has been little effort expended in the direction of applying knowledge from laboratory experiments and lunar exploration to the asteroids. Given the increased knowledge being obtained about the solar wind and the small particle population in the solar system and particularly in the asteroid belt by Pioneer F, there should be sufficient information to develop a realistic model for asteroid regoliths.

There will certainly be other areas of inquiry developed concerning asteroid spins, catastrophic collisional processes, internal conditions, resonances, and so on.

4.3 Future Needs

There are some current problems concerning asteroids for which we may confidently expect solutions to be developed prior to space missions. Such results can obviate the need for studying those problems by missions and also change the priorities for studying other related problems. There is also a set of problems which we can be quite sure will have priority until missions are undertaken. It is important to specify the latter set of problems, because they are most relevant to targeting priorities.

There is little likelihood that asteroids fainter than absolute magnitude 13 or 14 will be observed by ground based techniques in any great number. Although a few small Mars-crossing objects will continue to be studied, and an occasional special faint asteroid farther out, detailed observations of a statistical sample of these small bodies cannot practically be done. Hence, if there are size-dependent differences in mineralogy and other characteristics at these small sizes, they will remain only sparsely sampled.

Very important to solving the "Grand Canyon problem" are studies of mineralogical differences on individual asteroids because of the implications for accretionary sequences and differentiation processes. However, present indications suggest that color and albedo differences as a function of rotation are weak and difficult to observe. While there is indirect evidence to be interpreted (comparative studies of Hirayama families, etc.), definitive studies of such compositional heterogeniety must await space missions.

Although we will have gross information on diameters, shapes, rotation periods, and pole directions for many asteroids, there may be purposes for which we will need higher accuracy than can be obtained from earth. We may wish to study asteroid topography or small changes in spin produced by collisions or other causes; these require more precise measurements.

Masses of asteroids, and hence, densities, will in all probability remain virtually unknown until we send spacecraft to their vicinity. The same is true for the details of their gravitational fields which are so useful for studying the properties of asteroid interiors.

The remote-sensing mineralogical identification programs have fundamental limitations. Present indications suggest that as many as a third of the asteroids may not have sufficient absorption band structure to permit even gross mineralogical identification, although many possibilities can be definitively ruled out for them. Even for the remainder, it can be expected that only the major minerals can be identified, and even those will be weighted towards certain kinds of minerals particularly amenable to such study, such as the pyroxenes. Although these coarse studies will be very useful, any kind of analysis of minor or trace components of asteroid rocks or even chemical composition, must await a landing.

5. MISSION CONSIDERATIONS

There are three major classes of asteroid missions possible: lander/sample return, orbiters, and flybys. The detailed chemical, mineralogical, and structural data required to provide maximum understanding of the asteroids and their history require a lander mission with sophisticated equipment for automated analysis and/or a sample return capability. The analogy with lunar exploration is obvious. By the same token, the spacecraft and launch vehicle requirements for such missions place them in a very advanced class and in a concomittant time frame. The expense of such missions makes it mandatory to greatly increase our understanding of the asteroids and therefore our target selection capability prior to mission initiation.

Rendezvous with an asteroid permits all of the same measurements that can be obtained from a fly-by and more as well. The potential advantages are chiefly these: 1) time variable phenomena can be studies; 2) those kind of observations which require long durations to build up precision can be made; 3) complete mapping coverage of the asteroid is possible; and 4) closer approach is possible. However, there are relatively few time-variable phenomena to study on asteroids. Radiometric studies of a particular region as it passes from "day" into "night" and back again are best carried out from an orbiter, although gross day/night characteristics can be determined from fly-by. If there were significant observable changes as a function of solar distance for an asteroid in a highly elliptical orbit, they could be studied only by an orbiter; however, it is doubtful that there will be important changes of that sort.

Detailed measurements of particles and fields in the vicinity of an asteroid can best be done from orbit. This includes its gravity field which can be measured precisely only by staying near the asteroid for a long time -- it must be remembered that most asteroidal gravity fields are very weak.

One might hope to gain information not only on the mass, but also the moment of inertia, and higher order terms of the gravity fields which can yield information on the internal structure of the asteroid. Very precise determination of rotation periods and axis orientations likewise require a long stay, as does very precise measurement of the asteroid velocity vector.

Flybys permit close-up observation of an asteroid but for only a short duration. Spatial resolution is vastly improved over observations made from the earth. Also, the viewing geometry is different and varies (rapidly); large phase angles can be obtained. In addition, the mere proximity to the asteroid enhances several important measurements; radar observations are vastly simpler and the gravitational field of the asteroid will influence the spacecraft trajectory in a diagnostic fashion. Finally, the space environment of the asteroid including solar wind characteristics and small particle populations, can be directly measured and sampled.

Obviously, the chief advantage of a flyby is the possibility to make various remote-sensing kinds of observations with high spatial resolution. The diameter and physical shape of the asteroid can be precisely determined. Much of the asteroid can be precisely mapped by imagery during-fly-by, although if the relative velocity between spacecraft and asteroid is high and observing time at high resolution is restricted to less than half the rotation period of the asteroid, then less than complete coverage will be obtained. It is of high scientific interest to study crater populations to infer the impact and collisional history, and to study the rate of mass loss from asteroid surfaces. Indications of volcanic activity, or other internal processes, would be of the greatest interest, although they are not expected. The topography, apart from craters, may indicate stresses due to collisions, rotational braking or cooling. Also catastrophic fragmentation processes should have left their mark on surface topography and asteroid shape.

In addition to albedo and topographic maps obtained from imagery, near-IR mineralogical mapping, radiometric mapping, and bistatic radar mapping will each provide useful information on regolith structure and mineralogy. Appropriate instrumentation and techniques can also yield information on the magnetic field, if any. This should not be ruled out in view of evidence for remanent magnetism in some meteorites.

The advantages of orbiters over flybys is not so great for asteroids as it is for planetary exploration. As described above, the chief advantage of an orbiter is that it permits study of time-variable phenomena; but these are far less important for asteroids than for planets. Orbiters also permit a longer stay for the purposes of photographic mapping, which is more important for large planets than it is for the small asteroids. With judicious planning, a significant fraction of an asteroid can be mapped by a fly-by and observations can be made at a variety of solar phase angles. Although the gravity field cannot be mapped in detail by a fly-by, it should be possible to measure it well enough to provide a reasonably accurate value for the mean density which is the most important quantity.

We already know that measureable asteroid characteristics differ widely (color and inferred mineralogy; albedo; degree of fragmentation; rotation period; photometric phase effects; diameter; possibly density; etc.). These differences reflect different early conditions and different processes operating in different parts of the solar system, and different evolutionary histories affecting different asteroids through special circumstances (e.g. major collisions) or factors related to asteroidal characteristics (e.g. regolith development processes correlated with size). Detailed studies of a single asteroid will probably only have significant meaning in the context of comparative studies; hence such comparative studies (treating the asteroid belt as a planet to be explored) should precede orbiter or sample-analysis missions in order that the asteroid selected for sampling will best answer the fundamental questions. Thus, a multiple fly-by mission involving the comparison of a number of different asteroids may be more advantageous than a lander or sample return mission since with our present state of knowledge we lack any reason for choosing a single asteroid as a source of the varied samples we would like. In all probability, a sample returned would be found to be identical to meteorites already extant in museums, or at least would fall in an unsurprising fashion somewhere along the spectrum of meteorite types already known.

6. ASTEROID TARGET SELECTION

A strategy for applying scientific criteria to the selection of asteroids for mission evaluation must be a dynamic one since information concerning the asteroids is continually being augmented. It should be sufficiently flexible to accomodate new data as it is obtained and also sufficiently flexible to adapt to surprises and departures from current expectations.

The discussion in earlier chapters demonstrates that the most important parameter concerning asteroids is composition. The questions of greatest interest relate to how this composition varies from place to place in the solar system, especially as a function of semi-major axis. Variation of composition as a function of place in the solar system at time of formation is most directly tested by comparisons of composition as a function of semi-major axis and the proper orbital elements e and i. Current orbits are not necessarily representative of the proper elements, but the semi-major axis is fixed. When a minor planet is permanently perturbed, the a, e, and i of the new orbit must bear a fixed relationship to the original orbit. Thus examination of the proper orbit is more directly related to the original orbit during early solar system history than is the current orbit. Also of great interest is how composition varies as a function of size, and in particular as a function of depth within the largest asteroids. A variety of secondary goals have also been discussed.

Let us examine how the ground-based observable parameters relate to these goals. Clearly, the parameters which are indicative of composition are: density, albedo, and (especially) spectral reflectivity. The first of these is a parameter which is known for only two asteroids and for which there is little likelihood of extension to other asteroids by ground-based techniques. The second two parameters can be combined into the term spectral albedo, and is the chief observable relating to composition.

Composition as a function of depth in an asteroid is most effectively studied by looking at asteroidal fragments. The most direct observable is to look for color variations or perhaps albedo variations of asteroids as a function of rotational phase angle. To date significant color variations have been found only for 4 Vesta and 6 Hebe, and those were of small amplitude (especially for Vesta). Albedo variations are more commonly observed, although they may be less important unless correlated with simultaneous color changes; however, no one has specifically and carefully studied asteroid lightcurves with the aim of isolating albedo differences. Although most asteroidal light-curve variation is believed due to non-sphericity because of the double-peaked character of the curves, a significant portion of the variation may be due to albedo differences across asteroid surfaces, recognized by odd terms in the expansion of the light-curve (Lacis and Fix, 1971). Using available light-curves, a first, and incomplete examination of the problem has been made (Chapman, 1971). The results are included in Figure 3 (Albedo Variations With Rotation) but are not shown in the data sheets.

Other parameters reflecting asteroidal fragmentation (although not necessarily indicative of compositional variation within the fragments), are light-curve amplitude (and perhaps "raggedness", if not due to albedo variations), and membership in Hirayama families. Presumably rotation periods are affected by catastrophic collisions, but the manner in which they are correlated is uncertain. Asteroids having very short rotation periods may be more likely to be fragments.

Other observables of still less importance to the fundamental scientific goals are the phase variation of various photometric parameters; possibly polarization is more important to the extent that it is indicative of asteroid albedo. Precisely measured diameters are of little importance (except again as they relate to albedo); should asteroid masses be determined then the diameter is very important for purposes of determining density.

To summarize, in selecting priority targets the highest weight should be given to characteristics of spectral reflectivity) variations with rotation. High weight should be given to albedo, especially extreme values. Medium weight should be given to albedo variations with rotation, large light-curve amplitudes, and family membership. Low weight should be given to extreme (especially rapid) rotations. Little or no weight should be given to other parameters.

It is most important to observe the asteroids with these important compositional characteristics as a function of semi-major axis (highest priority), diameter (high priority), and proper e and proper i (especially as related to probably extreme values of <u>a</u> in the early solar system, or large distances above the ecliptic). Therefore we want a variety of asteroids which span important ranges of both distance from the sun and diameter which hopefully also have a variety of implied compositions and many of which have evidence for having exposed their interiors as a result of catastrophic collisions. Asteroids should be observed over <u>at least</u> the range of 40 to 350 km diameter. It is important also to span the asteroid belt; the sample should include an asteroid inside of a = 2.4 and an asteroid with aphelion distance beyond 3.5 AU.

Thus, from the point of view of current knowledge about the asteroids, we believe that the major emphasis should be to get close to as many asteroids as possible, constrained by two criteria: 1) At least one major asteroid should be visited, the surface characteristics of which suggests possible differentiation; 2) A reasonably wide range of semi-major axes should be explored, particularly including at least one asteroid (preferably of bluish color) in an orbit reaching aphelion beyond 3.5 AU. Even these criteria should not be regarded as strict. One would probably not wish to give up the opportunity to visit six different asteroids on the same mission if meeting the above criteria reduced the number of targets to only two or three.

A compilation of all reliably known physical data about the asteroids is contained in the appendix. There is a data sheet for each of 118 asteroids for which information, in addition to orbital parameters and magnitude, is available. Data that is considered unreliable (primarily old data such as results of photographic photometry) have been omitted. The information is up to date as of June, 1972 and includes the following parameters: the absolute B magnitude; B-V and U-B colors observed as a function of phase angle, also as reduced to 5° phase using lunar phase corrections; a description of asteroid color derived from reliable measurements of all kinds; several descriptions of the spectral reflectivity curve; phase factors for UBV magnitudes and colors; characteristics of the polarization versus phase curve; light-curve characteristics, including period, minimum and maximum amplitude, relative proportion of variability due to albedo differences and shape, and implied axis orientation; mass; diameter; albedo, proper orbital elements; and family membership. The appendix identifies the asteroids by name and by their assigned number. For convenience, subsequent tables in the body of the report identify the asteroids by number only.

The 118 asteroids have been segregrated into broad value ranges for each of the most significant parameters. Figure 1 contains the groupings for the orbital parameters. The ranges of semi-major axis, a, were selected to provide sets of asteroids which vary in distance from the approximate center of the belt. The eccentricities have been divided into four somewhat arbitrary categories spanning the known values to indicate the degree to which r_p or r_a will differ from a*. Similarly, the inclination of asteroidal orbits have been arbitrarily grouped. The asteroids which fall into a given category are identified by their assigned numbers which are arranged in ascending order to assist in the location of any particular body.

Figure 2 presents the known diameter and magnitude information in a manner similar to Figure 1. The ranges of magnitudes have been selected to roughly correspond to the ranges of measured diameters on the basis of Anders' formula.

$$\text{Log } D = 3.686 - 0.2B$$

where D is the diameter and B is the absolute magnitude. This relationship is very, very approximate and tends to underestimate (note that some asteroids of known diameter fall in a non-predicted magnitude class). It should be considered only as a rough guide to the size class when no direct measurements are available.

---

* $r_p = a\ (1-e)$; $r_a = a\ (1+e)$

SEMI-MAJOR AXIS	$a < 2.0$ $3.6 < a$	$2.0 < a < 2.4$ $3.2 < a < 3.6$	$2.4 < a < 2.6$ $3.0 < a < 3.2$	$2.6 < a < 3.0$
	433, 624, 911, 1437, 1566, 1620	4, 7, 8, 9, 12, 18, 27, 30, 40 43, 51, 60, 80, 92, 115, 122 186, 230, 337, 341, 345, 364 540, 554, 753	5, 6, 10, 11, 13, 14, 17, 19 20, 21, 24, 25, 29, 31, 32, 42 44, 52, 57, 62, 79, 89, 91, 95 162, 182, 192, 196, 268, 372 402, 409, 451, 478, 511, 704 976, 1043, 1287, 1291	1, 2, 3, 15, 16, 22, 23, 28, 34 37, 38, 39, 45, 54, 61, 64, 68 69, 70, 77, 78, 82, 85, 93, 110 116, 124, 179, 258, 321, 324, 349, 354, 356, 380, 385, 481 485, 498, 510, 532, 563, 658 674, 675, 779, 984
ECCENTRICITY	$1 > e > 0.25$	$0.25 > e > 0.2$	$0.2 > e > 0.15$	$0.15 > e > 0$
	2, 4, 23, 324, 1566, 1620	3, 5, 7, 25, 31, 60, 78, 82 162, 192, 356, 372, 433, 532 563, 753	6, 12, 14, 18, 20, 24, 27, 28 38, 42, 44, 54, 64, 69, 70, 79 80, 85, 115, 116, 182, 258, 268, 337, 364, 385, 485, 498 510, 511, 674, 675, 779, 976 984	1, 8, 9, 10, 11, 13, 15, 16 17, 19, 21, 22, 29, 30, 32 34, 37, 39, 40, 43, 45, 51 52, 57, 61, 68, 77, 89, 91 92, 93, 95, 110, 122, 124 179, 186, 196, 230, 321, 341 345, 349, 354, 380, 402, 409 451, 478, 481, 540, 554, 658 704, 1043, 1287, 1291
INCLINATION	$i > 10°$	$10° > i > 7.5°$	$7.5° > i > 5°$	$5° > i > 0$
	2, 3, 6, 13, 15, 18, 22, 25 31, 51, 54, 57, 61, 70, 85 89, 95, 115, 185, 230, 258 324, 345, 354, 372, 385, 402 409, 433, 451, 478, 485, 511 532, 674, 675, 704, 779, 984 1287, 1566, 1620	1, 12, 14, 23, 28, 38, 39, 42 68, 78, 80, 92, 93, 179, 337 349, 356, 481, 498, 510, 563 753, 976, 1043, 1291	4, 7, 8, 10, 29, 32, 34, 45 52, 79, 110, 162, 192, 196 341, 364, 380, 540	5, 9, 11, 16, 17, 19, 20, 21 24, 27, 30, 37, 40, 43, 44 60, 62, 64, 77, 82, 91, 116 122, 124, 182, 268, 321, 554 658

FIGURE I. ASTEROID ORBITAL PARAMETERS

DIAMETER (THERMAL IR)	D > 400	400 > D > 260	260 > D > 170	170 > D > 130	130 > D
	1, 2, 4	3, 7, 19, 324	6, 8, 15, 16	9, 18, 20, 25, 39, 44 68, 89, 192	5, 27, 80, 674
ABSOLUTE MAGNITUDE	B < 5.4	5.4 < B < 6.4	6.4 < B < 7.3	7.3 < B < 7.9	7.9 < B
	1, 4	2, 15	3, 6, 7, 9, 10, 16, 29 349, 511	8, 11, 14, 18, 20, 22 31, 39, 52, 196, 354 704	5, 12, 13, 17, 19, 21 23, 24, 25, 27, 28, 30 32, 34, 35, 37, 38, 40 42, 43, 44, 45, 51, 54 57, 60, 61, 62, 64, 68 69, 70, 77, 78, 79, 80 82, 85, 89, 91, 92, 93 95, 110, 115, 116, 122 124, 162, 179, 182, 186 192, 230, 258, 268, 321 324, 337, 341, 345, 356 364, 372, 380, 385, 402 409, 433, 451, 478, 481 485, 498, 510, 532, 540 554, 563, 624, 658, 674 675, 753, 779, 911, 976 984, 1043, 1287, 1291 1437, 1566, 1620

FIGURE 2. ASTEROID SIZE AND MAGNITUDE

The asteroid data which bear upon composition are contained in Figure 3. The most interesting characteristic, spectral reflectivity (as previously discussed), heads the list with rotation period coming last as the least interesting. Each category of the observed characteristics has been separated into ranges of values or classes with the more interesting asteroids appearing in the left hand column. The existence of band structure in the spectral reflectivity curves has been classified as more interesting than curves which exhibit a flat or sloping character although the interpretation of band structure to date is limited (Chapman 1971). Extreme values of the thermal IR albedo have been given higher weight than median values. Similarly large values of the light-curve amplitude, large variations of albedo with rotation, and extreme values of the light-curve amplitude were deemed more interesting. Asteroid groupings have also been included in this table. While such groupings are not direct evidence of their compositional nature, the relationship of asteroid position to sources of meteorites or to planets has been the basis for speculative inferences on composition.

As before, within each subcategory the asteroids are arranged in ascending numerical order for ease of location. The categorization in Figure 3 is very gross and should be supplemented with reference to the individual data sheets in any final selection process. However, Figure 3 can be used to obtain a rough total ranking of relative compositional and surface interest.

The categories were assigned ranking letters A, B, C, C, C and D from top to bottom while the ranges were numbered 1, 2 and (where applicable) 3 from left to right. Each asteroid was then classified by its "matrix" designation. For example, asteroid No. 4 is A1, B1, C3, C2, C1, D2; asteroid No. 5 is A1, B1, C2, C2, D1, etc. Those asteroids having three or more categories in which the range of interest was 1 were rated as

<table>
<tr><td rowspan="2">SPECTRAL REFLECTIVITY CURVES</td><td colspan="2">BAND STRUCTURE</td><td colspan="2">NO BAND STRUCTURE</td></tr>
<tr><td colspan="2">3, 4, 5, 6, 7, 12, 14, 17, 21, 29
39, 40, 43, 51, 68, 79, 82, 192
324, 409, 563</td><td colspan="2">1, 2, 10, 11, 13, 16, 93, 337, 356
554, 704</td></tr>
<tr><td rowspan="2">ALBEDO (THERMAL IR)</td><td colspan="2">0.1 ≤ A, A ≤ 0.02</td><td colspan="2">0.02 < A < 0.1</td></tr>
<tr><td colspan="2">4, 5, 15, 19, 39, 324</td><td colspan="2">1, 2, 6, 7, 20, 27, 68, 80, 674</td></tr>
<tr><td rowspan="2">LIGHT-CURVE AMPLITUDE</td><td>0.35 < Amax</td><td colspan="2">0.2 < Amax < 0.35</td><td>Amax < 0.2</td></tr>
<tr><td>15, 17, 18, 39, 44, 45
116, 186, 321, 345, 349
364, 433, 624, 984, 1437</td><td colspan="2">5, 6, 7, 9, 10, 12, 19
20, 22, 28, 40, 42, 61
89, 110, 162, 192, 196
354, 511, 911, 1566
1620</td><td>1, 2, 3, 4, 8, 11, 13, 14
16, 21, 23, 24, 25, 27
29, 30, 43, 51, 54, 60
78, 85, 230, 324, 451
532, 704, 753</td></tr>
<tr><td>ALBEDO VARIATIONS WITH ROTATION</td><td colspan="2"><u>ALBEDO COMPONENT STRONG</u>
1, 3, 4, 6, 7, 9, 16, 18, 23, 25
192, 196, 354

<u>SHAPE COMPONENT STRONG</u>
2, 15, 17, 19, 20, 22, 40, 61, 511</td><td colspan="2"><u>SOME ALBEDO COMPONENT</u>
39, 44, 321, 364</td></tr>
</table>

FIGURE 3. ASTEROID SURFACE AND COMPOSITIONAL PARAMETERS

ASTEROID GROUPS	ANDERS FAMILIES OF INTEREST 2, 25, 532 MARS CROSSERS 433, 1566, 1620 TROJAN ASTEROIDS 624, 911, 1437	ARNOLD AND WILLIAMS FAMILIES 1, 3, 4, 5, 8, 10, 11, 12, 13, 14, 16 17, 19, 21, 24, 28, 29, 37, 38, 39, 42 43, 44, 62, 68, 70, 77, 79, 82, 85, 92 93, 110, 192, 258, 268, 321, 337, 341 364, 380, 409, 481, 510, 540, 554 563, 658, 674, 704, 753, 779, 984 1287, 1291
LIGHT-CURVE (ROTATION) PERIOD	$15 \leq P$, $P \leq 4$	$4 < P < 15$
	5, 10, 28, 60, 321, 532 1437, 1566	1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 13 14, 15, 16, 17, 18, 19, 20, 21, 22 23, 24, 25, 27, 29, 30, 39, 40, 43 44, 51, 54, 61, 78, 85, 89, 110, 116 162, 186, 192, 196, 230, 324, 345 349, 354, 364, 433, 511, 624, 753 911, 984, 1620

FIGURE 3 (CON'T.) ASTEROID SURFACE AND COMPOSITIONAL PARAMETERS

highest interest; those with two categories with interest 1 were rated high interest and so on. This summary interest rating is shown in Figure 4. Figure 5 shows the categorical rankings for the asteroids in the highest interest groups. The individual ratings (1 = high, 2 - lower) for each category are indicated. Once again it should be emphasized that Figures 1-5 are guides to asteroid selection and multiple asteroid mission relative rating but should not be taken too literally.

The use of these selection guides can perhaps be best illustrated by several examples. Possible multiple asteroid missions can be found by selecting an initial target and running nominal trajectories to that target and beyond with a "search radius" which is defined by the propulsion system and the maneuvering ΔV. The tubular region of space which results can then be searched for other asteroids which might be available as secondary, tertiary, etc. targets. The selection of initial targets can be made on the basis fo the guidelines set out in this report. As previously stated, at least one major asteroid should be visited. The largest asteroids (Figure 2) are 1, 2, 4; 7, 19, 324. The relative compositional interest of these six is 4; 2, 7, 19, 324; 1 (Figure 4) and asteroids 2, 4, 324 have high eccentricity while asteroids 2, 324 are highly inclined (Figure 1). Thus, an approximate ranking of initial target major asteroids would be 4, 2, 324, 7, 19 and 1. This set contains Pallas (No. 2) which has a perihelion of 2.06 AU, an aphelion of 3.48 and is blue (color curve B3), thus partially satisfying the second constraint (see page 34). An examination of Figure 1 and the data sheets shows that 122 and 1437 are the only other "blue" asteroids with an aphelion greater than 3.48. Specific diameters for these latter two asteroids are not known but the magnitudes (Figure 2) indicate that they are small ($D < 100$ km) and therefore of potential interest since we wish to explore a range of diameters. Small asteroids with high compositional interest include 5, 17, 1437, 25, 321, 433, 624 and 1566; another set of possible initial targets. Other groupings

1	2	3	4
4, 5, 15, 17 39, 1437	2, 3, 6, 7, 18, 19 25, 40, 192, 321 324, 433, 532, 624 1566	1, 9, 10, 12, 14, 16 20, 21, 22, 23, 28, 29 43, 44, 45, 51, 60, 61 68, 79, 82, 116, 186 196, 345, 349, 354 364, 409, 511, 563 911, 984, 1620	8, 11, 13, 24, 27, 30 37, 38, 42, 54, 62, 70 77, 78, 80, 85, 89, 92 93, 110, 162, 230, 258 268, 337, 341, 356 380, 481, 510, 540 554, 658, 674, 704 753, 779, 1287, 1291

FIGURE 4. RELATIVE INTEREST GROUPING BASED ON SURFACE & COMPOSITIONAL CHARACTERISTICS.

Asteroid Number	Name	Spectral Reflectivity	Albedo	Light-Curve Amplitude	Albedo Variation	Groups	Light-Curve Period
4	Vesta	1	1		1	2	2
5	Astraea	1	1	2		2	1
15	Eunomia		1	1	1		2
17	Thetis	1		1	1	2	2
39	Laetitia	1	1	1	2	2	2
1437	Diomedes			1	1	1	
2	Pallas	2	2		1	1	2
3	Juno	1			1	2	2
6	Hebe	1	2	2	1		2
7	Iris	1	2	2	1		2
18	Melpomene			1	1		2
19	Fortuna		1	2	1	2	2
25	Phocaea				1	1	2
40	Harmonia	1		2	1		2
192	Nausikaa	1		2	1	2	2
321	Florentina			1	2	2	1
324	Bamberga	1	1				2
433	Eros			1		1	2
532	Herculina					1	1
624	Hektor			1		1	2
1566	Icarus			2		1	1

FIGURE 5. INTEREST RATINGS FOR 21 ASTEROIDS

are possible but the fifteen asteroids mentioned above cover many of the ranges of parameters of interest and represent a set of good starting points for a multiple mission search.

The selection guides can also be used to provide a relative rating of multiple asteroid missions which have been selected on an apriori basis as being energetically possible. The largest listing of three asteroid opportunities is given by Brooks et al (1972). Four missions have been picked from that list to illustrate the rating process. Table 1 summarizes the missions and the ratings. Clearly 68-1-1293 has the highest compositional interest, targets two major asteroids and explores outside the ecliptic plane. The relative rating of the second and third ranked missions is less obvious, however. While two asteroids in 540-116-223 have a specific interest, the only data on 540 (Figure 3) is its family membership. Asteroid 1 has data in four categories and in addition is a major asteroid. Asteroid 544 in the second ranked mission has an aphelion of approximately 3.8 AU and an inclination of 11.2° which is more interesting than the orbital parameters for 223. The case for ranking 1156-116-223 fourth is fairly obvious.

The tradeoff between 67-1-544 and 540-116-223 should serve to reemphasize the need to examine and weight the detailed knowledge of each asteroid. The summary classifications can provide a rough ranking but a second careful iteration is required. These examples did not include consideration of the size, color, etc. of those asteroids which had no high priority data. Although these asteroids are not included in the data sheets such information may be available.

Despite the caveats and admonitions, the discussion and rough groupings in Figures 1-5 can provide a valuable guide to the selection of target asteroids and to the relative scientific

Mission (Asteroid No.'s)	68	1	1293	67	1	544	540	116	223	1156	116	223
Compositional Interest Rating	3	3	--	--	3	--	4	3	--	--	3	--
Size (Magnitude)	160	290	--	--	290	--	--	8.8 (D<100)	--	--	8.8 (D<100)	--
a	2.78	2.76	2.23	2.42	2.76	3.17	2.22	2.77	3.09	2.26	2.77	3.09
e	.142	.101	.271	.187	.101	.195	.138	.174	.121	.043	.174	.121
i	7.5	9.7	5.4	6.0	9.7	11.2	6.1	3.6	1.97	1.43	3.6	1.97
Mission Scientific Rating (Relative)		1			2			3			4	

TABLE I. RELATIVE RATING OF MULTIPLE MISSIONS ranking of candidate missions. A follow-on study to search for high interest asteroid missions is planned for the coming year. If this proves successful, consideration should be given to updating the tables and data sheets to include new observations and interpretations on an annual or biannual basis.