Identifying Relevant Scientific Goals in Planetary Exploration

JOHN P. HENNES* AND CHARLES V. FULMER†
The Boeing Company, Seattle, Wash.

The scientific goal of understanding the origin and evolution of the solar system has been examined in terms of the various processes that have led to the development of the solar system, planetary interiors and surfaces, and planetary atmospheres. A scientific rationale for identifying relevant goals and objectives in planetary exploration and an evaluation scheme for making value judgments are outlined and some particular examples are given. Analysis of outer planet exploration missions shows that an orbiter of Jupiter has a scientific value about 4 times that of a flyby of Jupiter and about 0.8 that of a fully instrumented entry probe into Jupiter. Missions and payloads can be selected rationally on the basis of their relevance to our fundamental scientific goals in space. Continued public support of solar system exploration can be encouraged by the participation of the space science community in a logical, publicly visible, and accountable selection analysis.

Introduction

THE diminishing pace of the space program and the increasing length and complexity of solar system exploration missions requires that greater effort be put into identifying relevant scientific goals and corresponding scientific measurement techniques and instrument payloads. The exploration of the outer solar system is beginning now. The opportunities for such missions are few and the costs high. Should single flyby "Grand Tours" be made or should effort be put into orbiters and entry probes? The choice of scientific missions or payloads should be based to a greater extent on the relevance of those missions or payloads to the fundamental scientific objectives for going into space, and not just on whether the technology already exists to carry out an experiment or whether something similar has been done before.

There are many reasons for exploring the solar system, including basic human questions of high philosophical and scientific content. The desire to learn where we come from, whether we are alone, or what is our future, has led to the formulation of scientific space goals in terms of answering the questions of the origin and evolution of the solar system, of life, and of the universe.[1,2] The task of scientific space program planners is to insure that the national space exploration program best approaches these goals. In this paper, we describe an approach to determining the value of various missions, instrument types, etc., in terms of how well those missions or instruments contribute to one of our nation's fundamental scientific space goals: understanding the origin and evolution of the solar system. Some of the results of this analysis are applied to outer planet missions. Other examinations of solar system exploration goals have also been reported.[3-8] The other major space goals (e.g., understanding the origin and evolution of life and of the large-scale universe, and understanding the processes that have shaped man's terrestrial environment) are not explicitly included in the evaluation. They do enter indirectly into the value assigned to some of the basic processes discussed below. A parallel study of astronomical observations has been made[9] using the origin and evolution of the universe as a primary goal. The study reported in this paper should be considered as an example of how our space program can be related to scientific goals and our conclusions, naturally, do not represent a consensus of the national space science community.

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* Space Sciences, Boeing Scientific Research Laboratories.

† Space Physics, Research Division; currently President, Geonics Inc., Seattle, Wash.

Solar System Evolution

Solar system regularities in orbit spacing, rotation periods, mean density, inclination and eccentricity, composition, etc., give some of the pertinent data making up the large body of evidence related to the development of the solar system. Similar collections of evidence can be assembled for the development of each particular planet, their atmospheres, and for the existence of life. Models of solar system development must be capable of explaining the regularities apparent in this evidence. There are, however, no theories of solar system origin and evolution existing today that do provide a comprehensive picture of its development.

Explanations of the origin and evolution of the solar system have followed the growth of our understanding of basic physical processes. Originally, gravitational forces were the only mechanism used to explain the generation of the solar system. Today, chemical and mineralogical processes, magnetic interactions and magnetohydrodynamics, and nuclear physics are also incorporated into solar system models. The most fundamental aspect of man's developing view of the cosmos is the acceptance of the hypothesis that what we now see is the result of a very long evolutionary process. There are no unexplainable features of the solar system which must be postulated, and a theory of natural development is indeed possible and can eventually be made quantitative.

Scientific theories relating to the origin and evolution of the solar system have been put forth since the 17th century. Reviews of the history of such theories are given by Page,[10] TerHaar and Cameron,[11] Witting,[3] and Williams and Cremin.[12] Commentary on more recent theories are also given by Whipple,[13] Cameron,[14] and TerHaar.[15] Theories of solar system origin and evolution can be categorized into two basic types—open and closed. Both theories have had their adherents, although today the closed system is the category being actively investigated. Originators of theories and solar system models and their relationship to these two theoretical categories are shown on Fig. 1.

A rough representation of current conceptions of a possible sequence of events in the formation of the solar system is given in Fig. 2. The figure shows a nebular model and indicates some of the steps or operations that must have acted to produce the solar system. If we examine the various proposed cosmogonical models we find that there are generally

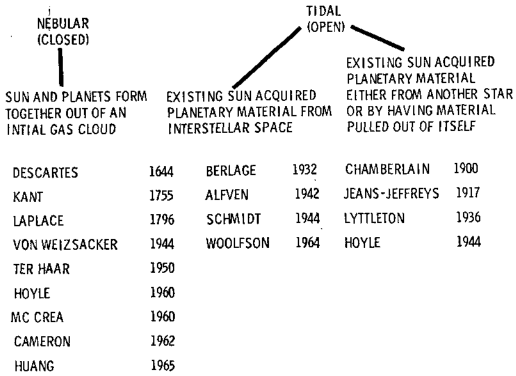


Fig. 1 Solar system cosmologies: the two principal hypotheses with some of the key individuals that have developed major models.

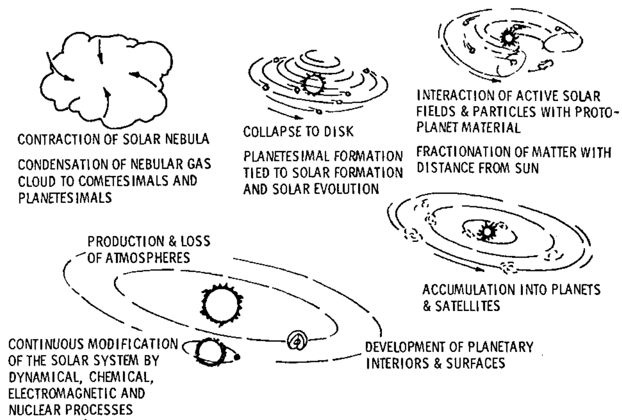


Fig. 2 Solar system formation: conceptual model of the nebular hypothesis indicating major processes that have produced our solar system.

Table 1 Processes operating in the origin and evolution of the solar system

A. DEVELOPMENT OF THE SOLAR SYSTEM

GENERAL CATEGORIES	DYNAMICAL DEVELOPMENT	CONDENSATION	FRACTIONATION	HEATING	SOLAR AND PLASMA	SATELLITES	SMALL BODIES	SOLAR SYSTEM MODIFICATION
SPECIFIC PROCESSES	DEVELOPMENT OF CONTRACTING SOLAR NEBULA	CONDENSATION OF NEBULAR CLOUDS INTO DROPS & GRAINS	FRACTIONATION OF SOLIDS BY COLLISION	GRAVITATIONAL HEATING OF NEBULA & DISK	EVOLUTION OF SUN TOWARDS MAIN SEQUENCE	FORMATION OF SATELLITE DISKS OR RINGS	BREAKUP OF PARENT BODIES TO FORM METEOROIDS	LOSS OF SATELLITES BY ESCAPE BREAKUP OR IMPACT
	COLLECTION OF MATTER INTO NEBULAR DISK	GROWTH OF DROPS AND GRAINS INTO COMETESIMALS	COSMOCHEMICAL FRACTIONATION BY PREFERENTIAL CONDENSATION	SOLAR THERMAL HEATING OF NEBULA & DISK	CHROMOSPHERIC ACTIVITY IN YOUNG STARS	GROWTH OF SATELLITES IN THE DISKS AND RINGS	VOLCANIC ERUPTION INTO SPACE TO FORM COMETS	ORBIT CHANGES OF SMALL BODIES BY PERTURBATION OR CAPTURE
	TRANSPORT AND ACCUMULATION OF MATTER IN NEBULAR DISK	GROWTH OF COMETESIMALS INTO PLANETESIMALS	COSMOCHEMICAL FRACTIONATION BY PREFERENTIAL LOSS	RADIOGENIC AND SOLAR PARTICLE HEATING	IONIZATION AND DISSOCIATION IN SOLAR NEBULA	CAPTURE OF SATELLITES	COMET PRESERVATION AT LIMITS OF SOLAR SYSTEM	COSMIC RAY PRODUCTION OF ELEMENTS IN METEOROIDS
	MODIFICATION OF ORBITS	AGGLOMERATION OF PLANETESIMALS INTO LARGE BODIES		MHD AND DISCHARGE HEATING IN NEBULAR GRAINS	COROTATION OF IONIZED MATTER IN MAGNETIC FIELD OF PRIMARY	GENERATION OF SATELLITES BY ROTATIONAL INSTABILITIES		CHARGED PARTICLE TRAPPING
	DEVELOPMENT OF ROTATIONAL CHARACTERISTICS OF BODIES	GRAVITATIONAL ACCRETION BY PLANETS			PRODUCTION AND TRANSPORT OF ENERGETIC SOLAR PARTICLES			ORBITAL AND ROTATIONAL CHANGES BY TIDAL DRAG
	ESCAPE OF MATTER FROM SOLAR SYSTEM				SPALLATION PRODUCTION OF LIGHT ELEMENTS			

B. DEVELOPMENT OF INTERIORS AND SURFACES OF BODIES

INTERNAL STRUCTURE	HEATING	MAGNETIC FIELDS	GEOLOGICAL DEVELOPMENT AND MODIFICATION			
GRAVITATIONAL DIFFERENTIATION	GRAVITATIONAL HEATING	DYNAMO GENERATION OF MAGNETIC FIELDS	SOLIDIFICATION BY THERMAL COOLING	CONTINENTAL DRIFT	SEDIMENTATION	ATMOSPHERIC EROSION
CHEMICAL FRACTIONATION	RADIOGENIC HEATING	INDUCTION OF MAGNETIC FIELD BY SOLAR WIND	ACCRETION	TECTONISM	METAMORPHISM	ICE AND WATER EROSION
PHASE TRANSFORMATION	CHEMICAL PHASE CHANGE HEATING	TEMPORAL CHANGES IN MAGNETIC FIELD	TIDAL FLEXING	DEFORMATION BY FOLDING AND FAULTING	VOLCANISM	METEORITIC EROSION
	TIDAL FRICTION HEATING		THERMAL CONVECTION	TENSIONAL FRACTURING	MODIFICATION BY IMPACT	CHEMICAL AND PHYSICAL WEATHERING
	IMPACT HEATING		DIFFERENTIAL ROTATION	ISOSTATIC ADJUSTMENT		BIOLOGICAL MODIFICATION
			EXPANSION OR CONTRACTION			

C. DEVELOPMENT OF PLANETARY ATMOSPHERES

GENERATION	CAPTURE	LOSS	CHEMICAL EVOLUTION	DYNAMICAL BEHAVIOR
OUTGASSING FROM THE INTERIOR	CAPTURE FROM THE SOLAR NEBULA	THERMAL EVAPORATION	CHEMICAL REACTIONS WITH CRUST	CIRCULATION OF OCEANS AND ATMOSPHERE
PRODUCTION BY COLLISIONAL HEATING AND RELEASE	CAPTURE FROM THE SOLAR WIND	SOLAR WIND SWEEPING	ATMOSPHERIC ELECTRICAL & PHOTOCHEMICAL REACTIONS	LOCAL WEATHER
	CAPTURE FROM SOLAR SYSTEM OBJECTS	ESCAPE BY ROTATIONAL INSTABILITY	BIOLOGICAL REACTIONS	UPPER ATMOSPHERE PROCESSES
		DISSIPATION BY COLLISIONAL HEATING		

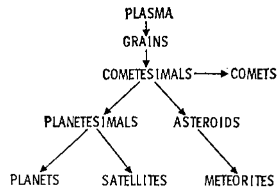


Fig. 3 Condensation sequence: Stages in solar system evolution resulting from various condensation processes (after Alfven[16]).

no critical tests that can be applied to eliminate any one model or theory. Each theory, because of its looseness, has sufficient freedom to permit incorporation of almost any new observational data. We propose that progress can be made, however, by trying to understand the elements making up the various theories.

These elements are the processes that have operated, and still operate, to produce the present configuration and properties of the solar system from its initial conditions. The processes, for instance, by which the solar nebular material became fractionated to produce dense terrestrial planets and gassy outer planets is a common element of all theories and must be understood in great detail if further progress is to be made in solar system cosmogony. Another set of processes is related to condensation of the planets from the original solar nebula. Figure 3, adapted from Alfven,[16] illustrates a sequence of condensation steps. Various condensation processes based on chemical, electromagnetic, and gravitational forces can act to produce the present bodies of the solar system. Any theory of origins combines many processes. What is clear is that a deeper understanding must be reached of the various processes that have operated and are operating in the solar system and that together constitute the actual model history of the solar system.

Identifying Scientific Goals

Space exploration does not permit a direct solution to the problem of the origin and evolution of the solar system. It does permit us to acquire much new quantitative information regarding important observable physical properties of planets and other bodies, and then to relate those observable properties to the dynamic processes that make up the cosmogonical models. To clarify these relationships we have established a space science rationale for planetary exploration directed towards the solution of the origin and evolution problems. This approach establishes the relationship between such things as instruments or missions and the physical processes. The method essentially consists of relating the different levels of scientific description, shown diagrammatically in Fig. 4, in terms of the relevancy between the different levels. With this method we can determine the relative value of various missions, measurement techniques, or instrument types. Value in this context is highest for those missions, instrument, etc. that contribute most to achieving the scientific goal.

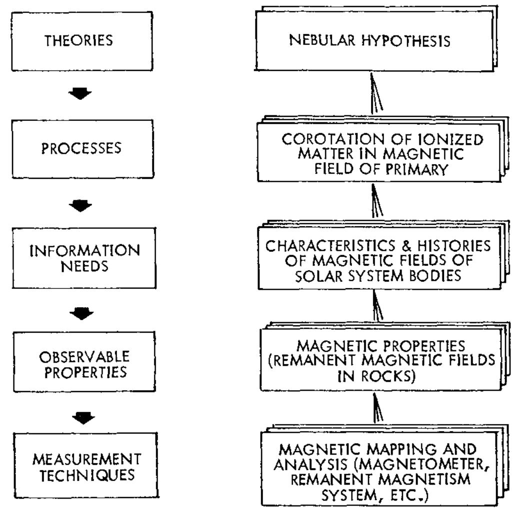


Fig. 4 Descriptive levels of a space exploration rationale, with a single chain example.

Rationale Terms

A process can be defined as a series of actions or operations producing a continuous change in time of a physical phenomenon. From an examination of all proposed solar system cosmogonical models, we have made a comprehensive list of 82 processes divided into three classes (Table 1). For any

Table 2 Observable properties of the solar system

OBSERVABLES	SPECIFIC PROPERTIES
ASTROMETRIC PROPERTIES	
1. ORBITAL PARAMETERS	EPHEMERIDES YEAR ECCENTRICITY INCLINATION
2. PLANETARY MOTIONS	ROTATIONS WOBBLE NUTATIONS LIBRATIONS
INTERIOR OR BULK PROPERTIES	
3. BULK MAGNETIC FIELDS	MAIN MAGNETIC FIELD FIELD VARIATIONS
4. OPTICAL DIMENSIONS	FIGURE SIZE FLATTENING COMETARY DIMENSIONS
5. GRAVITATIONAL PROPERTIES	MASS GEOID OR MASS DISTRIBUTION MOMENTS OF INERTIA SURFACE GRAVITY FIELD
6. MEAN DENSITY	MEAN DENSITY
7. THERMAL BUDGET	ENERGY INPUT ENERGY OUTFLOW
8. INTERNAL STRUCTURE	MANTLE-CORE-CRUST DENSITY COMETARY STRUCTURE
9. SEISMIC PROPERTIES	GROUND TREMORS MICROSEISMS QUAKES TRAVEL TIMES
SURFACE PROPERTIES AND MINOR BODY PROPERTIES	
10. COMPOSITION	CHEMICAL COMPOSITION ISOTOPIC ABUNDANCES RADIOACTIVE COMPOSITION REDOX
11. MAGNETIC PROPERTIES	MAGNETIC SUSCEPTIBILITY LOCAL FIELD VARIATIONS REMANENT MAGNETIC FIELD COMETARY MAGNETIC FIELD STRUCTURE
12. THERMAL PROPERTIES	TEMPERATURES TEMPERATURE GRADIENTS THERMAL CONDUCTIVITY SPECIFIC HEAT HEAT FLOW EMISSIVITY THERMAL EMISSION
13. SURFACE OPTICAL PROPERTIES	COLOR ALBEDO, LOCAL AND GLOBAL LUMINESCENCE FLUORESCENCE TONAL VARIATION PHOTOMETRIC FUNCTION
14. SURFACE IRRADIATION PROPERTIES	SOLAR SPECTRAL IRRADIANCE RADIATION ENVIRONMENT
15. PETROGRAPHIC PROPERTIES	MINEROLOGY CRYSTALLOGRAPHY
16. ELECTRICAL PROPERTIES	CONDUCTIVITY RESISTIVITY ELECTRIC FIELDS ION CONTENT
17. PHYSICAL PROPERTIES	PARTICLE SIZES POROSITY PERMEABILITY DENSITIES SORTING
18. MECHANICAL PROPERTIES	BEARING STRENGTH COHESIVENESS ANGLE OF REPOSE
19. STRUCTURAL PROPERTIES	FRACTURE FOLD STRUCTURE FAULT STRUCTURE
20. FORMATIONS	STRATIGRAPHY LITHOLOGY
21. TOPOGRAPHIC PROPERTIES	ELEVATION CURVATURE LAND FORMS CRATERS BLOCKS RIDGES
22. PHYSIOGRAPHIC PROPERTIES	PROFILES SLOPES BASINS ROUGHNESS
23. AGES	RELATIVE AGES OF ROCKS RELATIVE AGES OF FEATURES RADIOSOTOPE AGES
24. TEXTURAL PROPERTIES	FABRIC PATTERNS DISCONTINUITIES SURFACE POSITIONS COMETARY TAIL PATTERNS
25. HYDROLOGICAL PROPERTIES	MOISTURE PERMAFROST GROUND WATER GLACIATION
26. VOLCANIC PROPERTIES	FLOWS OUTGASSING SUBLIMATES
27. OCEANOLOGICAL PROPERTIES	WAVES TIDES COMPOSITION TEMPERATURE
28. BIOLOGICAL PROPERTIES	BIOLOGICAL PROPERTIES

Table 2 (continued)

OBSERVABLES	SPECIFIC PROPERTIES
PLANETARY ATMOSPHERIC PROPERTIES	
29. ATMOSPHERIC COMPOSITION	CHEMICAL COMPOSITION ISOTOPIC ABUNDANCES ION CONTENT
30. ATMOSPHERIC THERMAL PROPERTIES	TEMPERATURE THERMAL EMISSION RELEASED HEAT
31. ATMOSPHERIC PRESSURE	PRESSURE
32. ATMOSPHERIC DENSITY	DENSITY
33. ATMOSPHERIC MOISTURE	HUMIDITY PRECIPITATION
34. ATMOSPHERIC PARTICLES	CLOUDS AEROSOLS DUST
35. ATMOSPHERIC MOTIONS	WIND FIELD CIRCULATION PATTERNS
36. ATMOSPHERIC ELECTRICAL PROPERTIES	ELECTRICAL FIELDS DISCHARGES RADIO EMISSION EM-WAVE PROPAGATION
37. IONOSPHERIC PROPERTIES	ELECTRON DENSITY TRANSPORT RATES VARIATIONS
38. ATMOSPHERIC OPTICAL PROPERTIES	ATTENUATION AURORA AIRGLOW
39. EXOSPHERIC PROPERTIES	TEMPERATURE DENSITY COMPOSITION

OBSERVABLES	SPECIFIC PROPERTIES
EXTRAATMOSPHERIC AND INTERPLANETARY PROPERTIES	
40. MAGNETIC FIELDS IN SPACE	FIELDS VARIATIONS
41. GALACTIC COSMIC RAY PROPERTIES	COMPOSITION FLUX SPECTRUM
42. SOLAR PLASMA PROPERTIES	COMPOSITION DENSITY VELOCITY TEMPERATURE PRESSURE
43. SOLAR PARTICLE EVENT PROPERTIES	COMPOSITION FLUX SPECTRUM
44. TRAPPED RADIATION PROPERTIES	COMPOSITION FLUX SPECTRUM PITCH ANGLE ALBEDO PARTICLES
45. COSMIC DUST PROPERTIES	COMPOSITION MINEROLOGY DENSITIES FLUX VELOCITY DISTRIBUTION INFLUX RATE
46. SOLAR ROTATION	ROTATION DIFFERENTIAL ROTATION
47. SOLAR BULK PROPERTIES	OPTICAL FIGURE MASS MASS DISTRIBUTION MEAN DENSITY
48. SOLAR ATMOSPHERIC PROPERTIES	CHEMICAL COMPOSITION ISOTOPIC ABUNDANCE TEMPERATURE TEMPERATURE GRADIENTS SCALE HEIGHTS PRESSURE DENSITY

OBSERVABLES	SPECIFIC PROPERTIES
SOLAR AND STELLAR PROPERTIES	
49. SOLAR EMISSIONS	OPTICAL EMISSIONS X-RAY EMISSION RADIO EMISSION
50. SOLAR MAGNETIC PROPERTIES	LOCAL MAGNETIC FIELDS POLARITY CHANGES
51. SOLAR SUNSPOTS AND FLARES	LOCATIONS GROWTH SIZE TEMPERATURE MASS LOSS ETC.
52. SOLAR ACTIVE REGION PROPERTIES	LOCATIONS GROWTH PARTICLE DYNAMICS
53. SOLAR GRANULATION	CELL DIMENSIONS GRANULARITY SUPERGRANULARITY
54. SOLAR ATMOSPHERIC MOTIONS	WAVELENGTHS VELOCITIES WAVE NUMBERS (REYNOLDS, ETC.) CIRCULATION PATTERNS
55. ASTRONOMICAL PROPERTIES	STELLAR INTERSTELLAR OTHER EXTRASOLAR PROPERTIES

process, the emphasis is on the continuing action and not on the end points, which are the physical conditions at any given time. As we have seen, the nebular theory of the origin of the solar system is made up of a variety of processes operating on the original nebular cloud.

A process cannot be understood by making single observations of a system as it exists now. A sequence of observations in time, like a motion picture of a dynamic system, is needed to determine the continuing action of the process. In most cases there are no unique physical properties which reveal the nature of a process. Instead, information is needed about a variety of physical phenomena. To understand the process of how a satellite such as the moon might be captured, we need information about earth's rotational history, tidal drag and tidal histories, thermal histories, and so on. These information needs cannot be satisfied with a single observation. They are concerned with characteristics and histories of physical systems and deal with more generalized physical concepts than a specific physical property. Information needs may deal with such diverse matters as the characteristics and history of orbits, erosion features on the surface, and sinks or sources of atmospheric constituents. Many information needs have been identified but because of lack of space the complete table has been omitted here. The use or omission of a particular category or level of scientific description shown in Figure 4 is discussed in the next section.

The history of earth's rotation[17] is not directly observable. And yet, the observable physical properties of an object are the only parameters that we can determine directly. Our scientific techniques deal only with what exists now, the physical properties intrinsic to the system under study. Any information needed can thus only come from determining several observable physical properties, as listed in Table 2. The next step in our rationale approach is therefore to determine those various observable properties that contribute to acquiring the information needed to understand a process.

If the observable properties are established, then the connection of this logical sequence of scientific concepts to the space science exploration program becomes much simpler. A space exploration mission is designed to acquire quantitative information regarding the observable physical properties of an object, such as a planet, whereas it is not designed to prove a theory or establish any particular process.

Observable properties are determined by the application of various scientific measurement techniques. Measurement techniques are given in Table 3. It is important to distinguish between measurement techniques and instruments. The technique is what allows a correspondence to be drawn between the observable property intrinsic to the external physical system, and the instrument reading that is a part of the particular instrumental characteristics. A spectrometer, for instance, does not measure composition of an external source; it provides spectral data. The techniques of spectrometry allow the spectral data to be interpreted variously as composition, temperature, or pressure. The purpose of a spacecraft mission is to allow a variety of techniques to be applied. Finally, for each measurement technique, there are various instrument types that can be used with that technique (see also Table 3).

Space Exploration Evaluation

Having identified the space exploration rationale terms above, we must next describe how the quantitative elements of each step can be determined by a simple evaluation technique. Each process can be assigned a value describing the relative importance of the process in the cosmological scheme of things. This value, V_p, can only be assigned on a judgmental basis since it represents a disputable part of a larger cosmological theory. For example, the process by which the sun evolves toward a main sequence star is obviously of great importance to every nebular hypothesis but of lesser importance to an open system model in which the sun is postulated as pre-existing the formulation of a protoplanetary cloud. For each process there are a number of information needs which must be satisfied if the process is to be understood. Some information needs are highly relevant to understanding a process while others are less relevant. For example, in the preceding section the earth's rotational history was given as an information need related to the process of capture of satellites. If the moon was captured, then its tidal effect on the earth's rotation rate at the time of capture and thereafter would have been dramatic, and this highly relevant information should be recorded in the earth's geological history. We may define a relevancy factor, R_{np}, that describes numerically

Table 3 Measurement techniques and instrument categories for the exploration of the solar system

	Measurement technique	Instrument category
1.	VISIBLE IMAGING	MULTISPECTRAL PHOTO SYSTEM VISUAL INSPECTION PHOTO SYSTEM TV SYSTEM
2.	RADAR IMAGING	SIDE-LOOKING MONOSTATIC RADAR BISTATIC RADAR IMAGING
3.	MICROSCOPIC IMAGING	PETROGRAPHIC MICROSCOPE
4.	THERMAL IMAGING	IR MAPPING AND IMAGING SYSTEM
5.	SOLAR SPECTRAL IMAGING	SOLAR SPECTROHELIOGRAPH
6.	THERMAL RADIOMETRY	BOLOMETER IR RADIOMETER SCANNER IR STRIP RADIOMETER
7.	RADIO RADIOMETRY/ POLARIMETRY (PASSIVE)	MICROWAVE RADIOMETER SCANNER RF NOISE DETECTOR RF POLARIMETER
8.	OPTICAL RADIOMETRY/ POLARIMETRY	OPTICAL POLARIMETER PHOTOMETRY
9.	OPTICAL SPECTROMETRY OF ATMOSPHERE	UV SPECTROMETER IR SPECTROMETER (FAR) IR SPECTROMETER (NEAR) IR INTERFEROMETER SPECTROMETER VISIBLE SPECTROMETER
10.	OPTICAL SPECTROMETRY OF SURFACES	FLUORESCENT SPECTROMETER
11.	X AND GAMMA RAY SPECTROMETRY	GAMMA RAY SPECTROMETER X-RAY SPECTROMETER X-RAY FLUORESCENCE SPECTROMETER
12.	SPECTROMETRY OF SOLAR ATMOSPHERE	SOLAR SPECTROMETER (X-RAY–IR)
13.	CHARGED PARTICLE SPECTROMETRY OF SPACE	PLASMA PROBE CHARGED PARTICLE SPECTROMETER TRAPPED RAD DETECTOR COSMIC RAY DETECTOR
14.	CHARGED PARTICLE SPECTROMETRY OF SURFACES	ION CHAMBER NEUTRON-SCATTER DETECTOR GAMMA-GAMMA BACKSCATTER SYSTEM NEUTRON ACTIVATION SPECTROMETER ALPHA SCATTER SPECTROMETER
15.	ATMOSPHERIC SOUNDING	BOTTOMSIDE SOUNDER TOPSIDE SOUNDER DUAL FREQUENCY OCCULTATION SYSTEM S-BAND OCCULTATION SYSTEM
16.	SURFACE SOUNDING	LASER ALTIMETER RADAR ALTIMETER ALTIMETER (FROM GROUND) RADAR RANGING OR TRACKING SYSTEM
17.	TRACKING	STELLAR TRACKER ON PLANETARY SURFACE TRACKING AND RANGING RADAR TRACKING TRANSPONDER TRACKING AND RANGING LASER
18.	DIRECT ATMOSPHERIC COMPOSITIONAL SAMPLING	MASS SPECTROMETER FOR ATMOSPHERE ATMOSPHERIC GAS CHROMATOGRAPH SPECIAL GAS ANALYZER FOR ATMOSPHERE
19.	DIRECT ATMOSPHERIC METEOROLOGICAL SAMPLING	ACCELEROMETER HYGROMETER PRESSURE SENSOR TEMPERATURE SENSOR FOR THE ATMOSPHERE ANEMOMETER MICROPHONE ACOUSTIC DETECTORS
20.	MAGNETIC MAPPING AND ANALYSIS	MAGNETOMETER MAGNETIC SUSCEPTABILITY DETECTOR REMANENT MAGNETISM (TRM, ETC.) SYSTEM
21.	THERMAL ANALYSIS ON THE SURFACE	TEMPERATURE SENSOR FOR SOIL DIFFERENTIAL THERMAL ANALYZER THERMAL DIFFUSIVITY SYSTEM
22.	OPTICAL ANALYSIS ON THE SURFACE	OPTICAL ACTIVITY REFRACTOMETER THERMOLUMINESCENCE SYSTEM
23.	CHEMICAL/PHYSICAL ANALYSIS ON THE SURFACE	GAS CHROMATOGRAPH FOR SURFACE MASS SPECTROMETER FOR SURFACE X-RAY DIFFRACTOMETER SURFACE ELECTRIC FIELD METER
24.	MECHANICAL TESTING AND SAMPLING OF THE SURFACE	PENETROMETER AUGER-DRILL-SCOOP CORE DRILLER PARTICLE SIZE ANALYZER ACCELEROMETER (IMPACT)
25.	GRAVITATIONAL MAPPING	FALLING BALL GRAVIMETER PENDULUM GRAVIMETER
26.	SEISMIC PROBING	SEISMOMETER (PASSIVE) ACTIVE SEISMOMETER (REFLECTION AND REFRACTION) DIRECT TRAVEL-TIME SENSOR (EXPLOSIVE CHARGES)
27.	PARTICULATE ANALYSIS IN SPACE	COSMIC DUST DETECTOR
28.	ASTRONOMICAL MEASUREMENT TECHNIQUES	ASTRONOMICAL INSTRUMENTS FOR EXTRASOLAR SYSTEM OBSERVATIONS
29.	BIOLOGICAL MEASUREMENT TECHNIQUES	BIOSCIENCE INSTRUMENTS

the relevance of a particular information need, n, to capture process, p. In the example cited R_{np} would be large.

In this fashion we can relate each information need to each process by some relevancy factor, R_{np}; many would have zero relevance, of course. By summing the product of relevance of a given information need, n, to every process, p, with the relative value of the process, V_p, we then have a number that indicates the relative value of n, V_n. Figure 5 indicates this relationship and shows for each of the other steps a relevancy exists and a relative value can be computed. The value of the measurement technique, V_m, represents one possible end point of this sequence. Notice that these expressions are simply matrix multiplications of the relevancy matrices. The terms can thus be combined stepwise; for example,

$$R_{on}R_{np} = R_{op}$$

or

$$V_m = \sum_p R_{mp}V_p$$

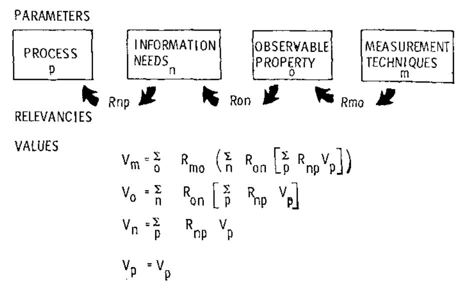


Fig. 5 Determining the value of entries in different levels of space exploration rationale requires associating a relevance between entries and a matrix combination of terms.

To assess the relevance R_{mp} of a particular measurement technique to a particular process, however, requires a large step in intuitive judgment covering many intermediate relationships. The approach of this study has been to break this large step into several smaller steps so that judgments can be made more easily, and traceability and visibility enhanced. In this way a variety of views of space scientists in specialized fields can be displayed and integrated into a total evaluation program.

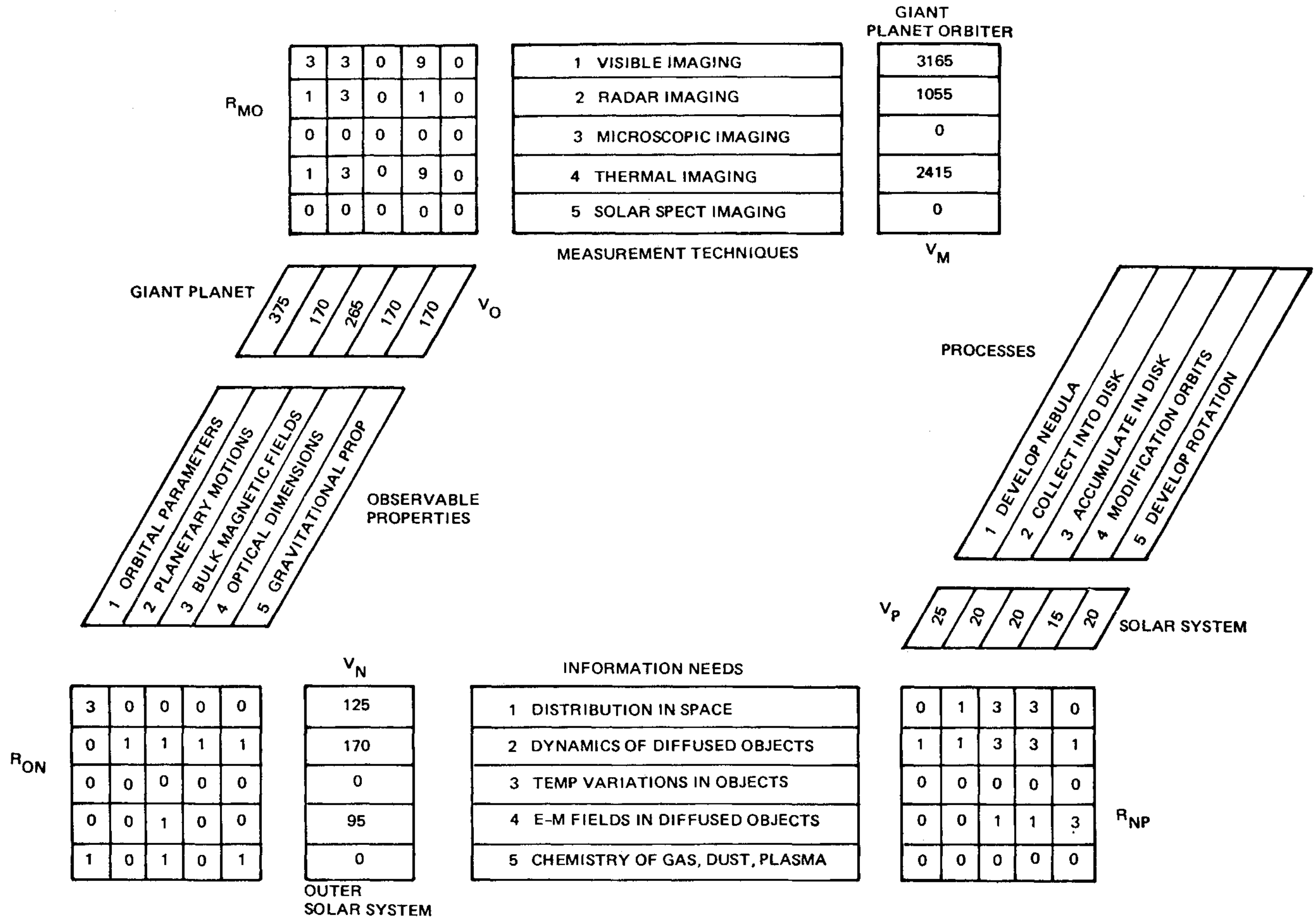
Figure 6 is an abbreviated numerical example of the space rationale evaluation described above. The first five items in each category are given (i.e., process, information need, observable, and measurement technique), and the relevancy matrices are filled with sample numbers for illustrative purposes. The value, as computed from the expressions given in Fig. 5, is then given for V_n, V_o, and V_m.

The scheme proposed here is a straightforward evaluation method. The principal difficulty of an evaluation of this type is that it must encompass a vast range of scientific material in a finite display so that the relationships can be grasped. The result is that a great deal of weight is put on the scientific judgment of the person assigning relevance factors at each step.

As the evaluation steps proceed clockwise around the categories and relevancy matrices of Fig. 6 the subject matter is made more specific. The relevance of visible imaging of the giant planets from an orbiter cannot be the same as from an entry probe, for instance. In addition, the relevance, and thereby the derived value, at each step is dependent on assumptions concerning previous steps.

The relevance of various information needs to the different processes are dependent on the cosmological views of solar system origins. The primary role of the nebular hypotheses is reflected in the process values, V_p, used in this study. Observable properties, however, are not only dependent on the cosmological assumptions making up the process values but are also dependent on similar kinds of assumptions about various bodies making up the solar system. For instance, the relevance of determining the gravitational properties of the satellites of Jupiter is partly dependent on our view of the cosmological significance of the satellite. As will be mentioned in the Results section, the satellites of the giant planets can be viewed as natural planetary systems and the significance of observations of them must reflect this view.

Notice that in the evaluation carried out here the quantity of information or number of data bits is not included. The emphasis is on the "usefulness" of the information. This emphasis comes in through the assignment of the relevance factors, a difficult subjective judgment. Subjectivity is inherent in all evaluation schemes. The background for the choice of processes and other concepts and a more complete description of the space exploration rationale analysis are contained in Ref. 18.



R_{MO}:

3	3	0	9	0
1	3	0	1	0
0	0	0	0	0
1	3	0	9	0
0	0	0	0	0

R_{ON}:

3	0	0	0	0
0	1	1	1	1
0	0	0	0	0
0	0	1	0	0
1	0	1	0	1

R_{NP}:

0	1	3	3	0
1	1	3	3	1
0	0	0	0	0
0	0	1	1	3
0	0	0	0	0

Fig. 6 A numerical example of the space rationale evaluation: clockwise steps combine relevance matrices with values to generate the value of the next level. Each level is more specific.

Outer Planet Exploration

The outer planet exploration opportunities coming in the late '70's provide man's best and rarest opportunity to obtain some firsthand information about the major bodies of the solar system—the giant planets Jupiter, Saturn, Uranus, Neptune and their major satellites.[19] Jupiter alone is equivalent to an entire solar system with its massive, gassy primary, and extended system of satellites. With few opportunities existing to explore the outer planets, what should be the scientific exploration program to best clarify our understanding of the origin and evolution of the solar system? To explore some of these possibilities and to illustrate the space exploration rationale analysis technique described in the preceding sections we have made a study of the scientific basis of missions to the outer planets.

Approach

The objective of this study has been to determine, for various targets in the outer solar system, the relative value of the observable properties and of the measurement techniques listed in Tables 2 and 3. The targets chosen are a) giant planets, b) Saturn's rings, c) satellites (of the giant planets) and Pluto, d) interplanetary space, and e) deep space (interplanetary plus out-of-the-ecliptic or out-of-the-solar system). Each process in Table 1 was assigned a value, V_p, indicating its relative importance in constructing a cosmogonical model. This value, which is an intuitive assignment, is a combination of the intrinsic importance of the process and how well the process is already understood. Values have been assigned from 5 to 50.

Because of the limited nature of the example study used here as an illustration of the rationale approach, we have chosen to eliminate the intermediate step of determining information needs. As described previously, this is possible because the relevance of an observable o to a process p is simply the product of the relevance of information need n to process p times the relevance of observable o to information need n

$$R_{op} = R_{on} R_{np}$$

In this study, we have used the following scale of relevance:

$$R_{mo} \text{ and } R_{op} = 0, 1, 3, 9$$

Other relevancy scales could be chosen, such as linear scale of 0, 1, 2, 3 or a log scale of 0, 1, 10, 100. Some preliminary use of these scales indicates that the resulting rankings are not excessively sensitive to relevance scaling.

The computational scheme given in Fig. 5 is then used to determine the value of any particular observable property V_o or of some measurement technique V_m. In carrying out this analysis, a complete matrix display of the relevance of 55 possible observables (Table 2) to 83 processes (Table 1) was needed for each of the five targets listed previously. A similar set of steps was carried through for the measurement techniques but with separate evaluations needed for separate exploration modes such as flyby, orbiter, probe, or lander as appropriate.

Results

The results of the computer calculations of values V_o and V_m are given in Tables 4 and 5, respectively. Table 4 identifies the value V_o (divided by 100) of the observable properties

Table 4 Value of scientific objectives for the outer solar system

	OBSERVABLE PROPERTY	GIANT PLANETS	INTERPLANETARY	DEEP SPACE + INTERPLANETARY	SATURN'S RINGS	MAJOR SATELLITES
29	CHEMICAL AND ISOTOPIC COMPOSITION OF ATMOSPHERES	72				22A
28	BIOLOGICAL PROPERTIES	46				16
10	COMPOSITION OF THE BULK PLANET AND SURFACE	27			5	21
33	ATMOSPHERIC MOISTURE, PRECIPITATION, ETC.	22				14A
30	ATMOSPHERIC TEMPERATURES AND THERMAL PROPERTIES	21				7A
5	GRAVITATIONAL PROPERTIES (MASS, MOMENTS, DISTRIBUTION)	16			2	11
3	BULK MAGNETIC FIELDS	13				7
32	ATMOSPHERIC DENSITY	13				8A
31	ATMOSPHERIC PRESSURE	13				5A
2	PLANETARY ROTATION AND OTHER MOTIONS	12				4
7	THERMAL ENERGY BUDGET	11				2
8	INTERNAL STRUCTURE	10				9
40	MAGNETIC FIELDS IN INTERPLANETARY AND MAGNETOSPHERIC SPACE	9	6	13	1	5
4	OPTICAL DIMENSIONS OF SIZE AND SHAPE	9			2	3
35	ATMOSPHERIC MOTIONS	9				2A
44	TRAPPED RADIATION PROPERTIES	8				1
6	MEAN DENSITIES	7				13
39	EXOSPHERIC PROPERTIES	7				2A
12	THERMAL PROPERTIES OF THE DEEP ATMOSPHERE AND MAIN BODY	5				5
38	ATMOSPHERIC OPTICAL PROPERTIES	5				1A
34	ATMOSPHERIC CLOUDS, AEROSOL AND DUST PROPERTIES	4				1A
1	ORBITAL PARAMETERS OF PLANETS AND SATELLITES	4	3	3	6	3
13	SURFACE OPTICAL PROPERTIES	4			1	3
26	VOLCANIC PROPERTIES	4				4
23	AGES OF ROCKS, FEATURES, ETC.	4			2	16
45	COSMIC DUST PROPERTIES	3	3	5		3
9	SEISMIC PROPERTIES	3				7
11	MAGNETIC PROPERTIES OF SURFACE MATTER	3			2	3
37	IONOSPHERIC PROPERTIES	3				< 1A
42	SOLAR PLASMA PROPERTIES IN NEAR-PLANET AND DEEP SPACE	2	6	9		1
21	TOPOGRAPHIC PROPERTIES OF SURFACES	2				12
22	PHYSIOGRAPHIC PROPERTIES	2				8
41	GALACTIC COSMIC RAY PROPERTIES	2	2	3		< 1
43	SOLAR PARTICLE EVENT PROPERTIES	1	3	6		1
24	TEXTURAL PROPERTIES	< 1				9
15	PETROGRAPHIC PROPERTIES	< 1			2	7
20	FORMATIONS	< 1				5
–	OTHER PROPERTIES	2	2	1	5	17
	TOTAL VALUE OF DETERMINING ALL PROPERTIES	380	25	40	28	258

A = VALUE ASSUMING SOME ATMOSPHERE EXISTS

listed for the five outer-planet targets. Table 5 identifies the value V_m (divided by 1000) of the 29 measurement techniques listed for the same five outer-planet targets along with various operation modes—vis., flyby, orbiter, and probes. There are several qualifications that should be noted in using these tables.

a) *Giant planets* In this study the Jovian planets were assumed to be essentially fluid with no or minimal solid characteristics. In this sense they are like small stars. As a result, observables and measurement techniques related to atmospheres are emphasized over observations of possible deep interfaces on these giant planet producing such features as Jupiter's red spot.

b) *Satellites/Pluto* The satellites constitute a small fraction of the mass of the solar system but share many of its features. We have taken the position (such as held by Alfven[20]) that the major satellites of Jupiter, Saturn, and Uranus are the result of processes paralleling those that formed the entire solar system. Thus, a study of these satellite systems is in some ways of almost equal importance to a study of all the planets. Pluto, small and dense, is treated here as equivalent to another satellite, which perhaps it is according to the hypothesis that it represents an escaped satellite of Neptune. The assumption has been made that the largest satellites, such as Titan, have thin or frozen atmospheres and observations of these are given relatively high weighting. If such atmospheres are not present, then the value of the corresponding observables, indicated by the letter A in Table 4, will become smaller.

c) *Saturn's rings* The rings of Saturn are here treated as primary objects in the solar system. That is, they are assumed to have existed in this form since the beginning rather than being a result of a recent breakup. They could thus exhibit, on a small scale, characteristics reflecting some of the early processes of dynamical evolution that produced the regular solar system features now present. A slow flythrough with particle collection is assumed.

d) *Interplanetary space* Fields and particles, cosmic dust, meteoroids and asteroids all come in this category. It was assumed that there is no close encounter with an asteroid.

e) *Deep space* This category assumes an interplanetary phase plus passage to very distant regions of the solar system (>50 a.u.) or out of the ecliptic plane.

Conclusions

Scientific objectives of the outer planet exploration program can now be reduced to the determination of those observable properties ranked highest in Table 4. The objectives recommended by the Space Science Board[19] are indeed similar to this listing. It is from such a list of objectives that specific missions and payloads should be derived. The conclusions reached in this study are based on the evaluative judgment of just a few individuals. For a more comprehensive evaluation, a national cross-section of space scientists from a variety of fields should share in the judgments of relevance so that the full implications of each step are included in the values determined. In this way, after suitable refinement, an evaluation would result that represented a truly integrated and visible display of the rational direction for our national space program.

Observables

The values of the observables are given in Table 4. The summation at the bottom, although not necessarily equivalent to over-all value, indicates that exploration of the major satellites is of comparable importance to exploration of the giant planets themselves. Interplanetary observations are seen to be of minor importance compared with either planetary or satellite exploration. Hence, relatively low-cost Explorer or Pioneer-type spacecraft should be looked to for the bulk of interplanetary and deep space exploration. It can be seen in Table 4 that for all objects, knowledge of composition ranks very high. For Jupiter and the giant planets, the atmosphere is essentially all we can observe and thus atmospheric composition ranks very high. Similarly, other atmospheric properties rank relatively high for the gassy giant planets while surface observables are zero or low because the existence of a surface is doubtful and its observation extremely difficult.

For both satellites and giant planets, the bulk properties have medium-high values as they reveal many of the basic characteristics of the bodies and are related directly to many processes. For the satellites, high value also appears in many surface observables (topography, seismic properties, etc.) because of what they reveal about planet development.

Table 5 Relative scientific value of measurement techniques for missions to the outer solar system

MEASUREMENT TECHNIQUE	GIANT PLANET FLYBY	GIANT PLANET ORBITER	GIANT PLANET ENTRY PROBE	SATURN RING FLY-THROUGH	SATELLITE FLYBY	SATELLITE ORBITER	SATELLITE LANDER	INTERPLANETARY	DEEP SPACE
SPECTROSCOPY OF THE ATMOSPHERE (9)	22	71	163	2	8	38	38		
OPTICAL RADIOMETRY/POLARIMETRY (8)	11	15	13	1	6	12	11	2	3
RADIO RADIOMETRY/POLARIMETRY (7)	10	35	6	< 1	1	3	1		
MAGNETIC MAPPING (20)	8	23	3	1	1	16	8	15	25
ATMOSPHERIC SOUNDING (15)	7	30	25	< 1	7	20	4		
THERMAL RADIOMETRY (6)	7	25	5	< 1	1	12	3		
TRACKING (17)	6	38	5	2	3	26	4	5	9
PARTICLE SPECTROSCOPY IN SPACE (13)	5	22	2	1	1	5	1	7	22
SURFACE SOUNDING (16)	5	26	4	3	3	12	< 1		
GRAVITATIONAL MAPPING (25)	5	24	3		3	25	9		
RADAR IMAGING (2)	4	21	5	4	8	46	12		4
VISIBLE IMAGING (1)	4	28	4	4	8	64	35	6	8
THERMAL IMAGING (4)	4	22	3	3	6	23	4		
X-GAMMA RAY SPECTROSCOPY (11)	2	2	3	< 1	2	8	10		
DIRECT ATMOSPHERIC SAMPLING (18)	<1	< 1	130	5			38		
PARTICULATE ANALYSIS (27)	<1	3		5	<1	1	< 1	4	5
ATMOSPHERIC METEOROLOGY (19)			50				22		
BIOLOGICAL SAMPLING (29)			41				17		
MICROSCOPIC IMAGING (3)			17	4		1	13		
CHEMICAL AND PHYSICAL ANALYSES (23)				7		< 1	43		
PARTICLE SPECTROMETRY OF SURFACES (14)				1		2	16		
OPTICAL SPECTROSCOPY OF SURFACES (10)					3	17	20		
THERMAL ANALYSIS OF SURFACE (21)							16		
OPTICAL ANALYSIS ON THE SURFACE (22)							15		
SEISMIC PROBING (26)							15		
MECHANICAL TESTING AND SAMPLING (24)							7		
$\sum v_M$	101	386	482	45	61	331	361	39	76
$\left(\sum v_M^2\right)^{1/2}$	32	116	221	13	19	105	94	19	36

Measurement Techniques

The values of the measurement techniques in Table 5 are naturally related to the values of the observables they determine. Because of the emphasis on composition, spectroscopy ranks very high as a technique. Mass spectrometry or other direct compositional sampling techniques (Nos. 18 and 23) also rank high for probes and landers. For the giant planets, atmospheric techniques are all-important. The assumption that there is no accessible surface and therefore no long-term stable details of planetary features, other than the slowly changing great red spot of Jupiter, greatly reduces the value of imaging systems. The value they retain arises from their use in observation of atmospheric motions and patterns, planetary size and motions, etc. Not included is any judgment of the value of pictures to satisfy human curiosity. For the satellites, imaging has a very high value as it has with our own moon. Some of the measurement techniques with significant value for satellite observations, such as atmospheric sounding or spectroscopy, are based on the assumed presence of a thin atmosphere. In the absence of any atmosphere those items would either vanish or have greatly reduced value.

Note that the order of rank for orbiter techniques is not the same as for flyby. Repeated observations from orbit increase the usefulness of some techniques (imaging, tracking, etc.) more than others. Many measurement techniques are redundant, while others may be complementary. Visual imaging and radar imaging have large overlap in data returned, for instance, while magnetic mapping and charged particle mapping are strongly reinforcing. The mutual dependence of measurement techniques is not explicitly handled in the rationale scheme proposed here and this is a weakness of all quantitative space mission judgment proposals. In carrying out this study, value was determined with the assumption that any essential, mutually reinforcing observations would also be available. Particles and fields observations turn out to be of high value only when the interplanetary cruise portion of a mission is added to the planetary encounter portion.

Missions

Because of the overlap in instrument functions it is difficult to determine the total value of any particular mission type. If a spacecraft were to employ all of the measurement techniques listed then the total value might be proportional to the linear sum of the individual values. These summations were given in Table 5 and are repeated, normalized to 1.0 for a giant planet flyby, in Table 6. Because the measurement techniques are not all independent other methods of computing mission value might be used. Table 5 also gives a root sum of the squares value. Although lower in absolute value than the linear sum, the relative ranking of the missions is essentially the same as in Table 6.

The high value of the entry probe is traceable to its ability to obtain compositional data. Orbiter techniques may be

Table 6 Relative value of outer-planet mission types

Giant planet entry probe	4.8
Giant planet orbiter	3.8
Satellite lander	3.6
Satellite orbiter	3.3
Giant planet flyby	1.0
Deep space probe	0.8
Satellite flyby	0.6
Interplanetary probe	0.4
Saturn fly-thru	0.4

incapable of obtaining data from a depth sufficient to represent the actual gross atmospheric composition. The importance of entry probes as identified here is in contrast to the current discussion of outer planet missions where, despite the Space Science Board's urgings,[19] only flybys and, secondarily, orbiters are being considered.

The importance of satellite observations is also evident in the tables. These too are not a significant part of current planning. However, a grand tour of a close encounter with a major satellite of each planet would be of value almost equal to a grand tour of their primaries.

Launch opportunities for Jupiter orbiters, Jupiter entry probes, Io landers, etc. exist every 13 months, but opportunities for similar investigative missions to Saturn, Uranus, and Neptune are going to be rare. More consideration needs to be given to making even minimal investigations of Uranus, Neptune and their satellites by means of probes or orbiters during the Grand Tour period. Such a course would have to assume that regular opportunities to explore Jupiter and Saturn would also be used.

Summary

The capability of making rational, visible judgments or comparisons of missions and payloads should not be neglected. The particles and fields emphasis of the Pioneer F and G Jupiter missions, for instance, although needed on the grounds of engineering limitations, should not be used to justify a similar emphasis on future missions. The significance of compositional data and the determination of various bulk properties requires suitable instrument payloads and will mean some difficult instrument trades as outer planet spacecraft weight limitations are reached.

Selection of missions and payloads, we have tried to demonstrate, can be made rationally on the basis of their relevance to our fundamental scientific goals in space. Much of the public's obvious dissatisfaction with our nation's space program, we feel, is because they have failed to find a rational structure to the development of space exploration and because the relevance of various space missions to our scientific goals and our fundamental human questions has not been made clear. This situation can be improved by an open, visible, and understandable accounting for the choices that are made in terms of how each choice relates to our larger human and scientific goals.

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