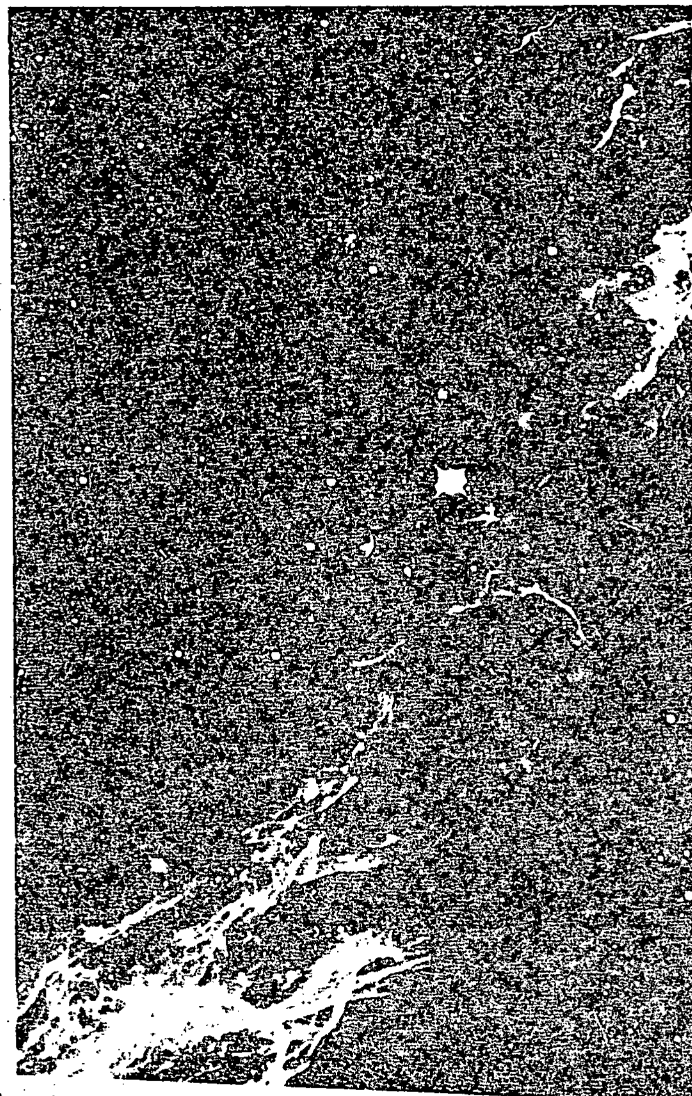

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A SURVEY OF CANDIDATE MISSIONS TO EXPLORE SATURN'S RINGS

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FOREWORD

This technical report covers work performed on one task of NASA contract number NASW-2144, Long Range Planning for Solar System Exploration. This study of objectives and methods for exploration of Saturn's ring system was initiated because it is a valuable precursor to the Saturn Orbiter Mission Study contract task. Work was completed in January 1972 prior to NASA's decision to replace the TOPS missions in 1977 (JSP) and 1979 (JUN) with a Mariner mission in 1977 to Jupiter and Saturn. The full impact of that decision on the contents of this report cannot be assessed until the Mariner spacecraft and this mission are better defined. However these two spacecraft are sufficiently similar in design philosophy and weight that only minor changes in the conclusions and recommendations might be expected. The Mariner spacecraft will be considered for Saturn orbiter missions in the subsequent study.

SUMMARY

The ring system around Saturn is one of the most striking features in the solar system. Exploration of the rings is required for an understanding of their origin and the hazard they represent to spacecraft near Saturn. In addition the rings may provide useful clues to the origin of the solar system. This study examines the problem of ring system exploration and recommends a sequence of missions which will collect the data required.

Earth-based observations have demonstrated that the rings are confined to the equatorial plane and are not more than several kilometers thick. The rings are translucent. The sizes of the ring particles are unknown. Earth-based observations cannot provide the data required to devise a ring system model that can form the basis of studies of the origin and evolution of the rings.

A payload analysis demonstrated that for first generation spacecraft the highest priority instruments are a photopolarimeter, an infrared radiometer and dual band radio occultation. These can be used on any flyby or orbiter spacecraft. Secondary instrument choices for a three-axis stabilized spacecraft such as TOPS are visual imagery and infrared spectroscopy. Knowledge of the size distribution and surface density of ring system particles will be improved by the data from these remote sensing instruments. A full 180° range in phase angle coverage is desired. Either deployed probes or orbiters (if the risk is acceptable) can also carry meteoroid detectors to directly measure the particle mass distribution and the composition of the rings. Some ring system properties such as the shape and structure of individual particles and the variation in orbital parameters must be evaluated by a spacecraft in an equatorial,

circular orbit. This second generation spacecraft should use the techniques of visual imagery and in-situ sample analysis.

For the five mission concepts which were identified, Table S-1 gives the exploration potential of each concept and the desired instruments. The 1977 JSP and 1978 JSUN constrained flyby opportunities do not have a full 180° of phase angle coverage since neither has a solar (or earth) occultation of the spacecraft by the rings (180° phase angle). For the JSP mission there is no 0° phase angle coverage either. From these constrained missions probe deployment is difficult. For an unconstrained mission three types (A, B and C)* of targeting were found, all of which have occultations at all ring radii between 1.20 and 2.27 R_s. The type A trajectory stays near the ecliptic plane and also has 0° phase angle coverage over this radial range; however, it can be used only if the saturnicentric declination of the Sun exceeds the declination of the approach asymptote. Probe deployment is also best done from a Type A trajectory and requires less than 50 m/sec.

A Type B trajectory has a 1.25 R_s periapse. However with a 90° argument of periapse, the ring plane is intersected at a distance of more than 2.5 R_s. This targeting results in a near minimum inclination. This trajectory allows examination of the rings at closer range, typically 0.1 R_s, but generally does not have both 0 and 180° phase angle coverage. The latter is also obtained if the solar declination is greater than that of the approach. When arrival conditions do not give occultations with either the Type A or B trajectories, the Type C may be used for this purpose. The spacecraft path is to a point in the ring plane just outside the rings and about 135° from the subsolar longitude. A high inclination (30-45°), which is always available, is chosen.

* A diagram of the different mission types is presented on page 34 of the report.

TABLE S-1 CANDIDATE SATURN RING MISSIONS

MISSION CONCEPT	EXPLORATION POTENTIAL	S/C TYPE	USEFUL INSTRUMENTATION	WEIGHT
1. Constrained Flyby	Limited Remote Sensing	TOPS	Photopolarimeter, IR Radiometer, TV	25 kg.
2. Unconstrained Flyby	Good Remote Sensing	Pioneer	Photopolarimeter, IR Radiometer, Radio Occultation	8
3. Elliptical Orbiter	Good In-situ and Remote Sensing	Pioneer	Photopolarimeter, IR Radiometer, Radio Occultation, Impact Mass Spectrometer	13
4. Circular Orbiter	Excellent In-situ and Remote Sensing	New	TV, Radar/Laser, Sample Analysis	90+
5. Deployed Probe	Engineering Data	TOPS Pioneer	Meteoroid Detector, Radio Occultation	2

For an elliptical orbiter a Type A approach trajectory can be used to put the spacecraft into an orbit with a periapse of 2.50 R_s. Again, excellent phase angle coverage is obtained. If ring intersections are desired the periapse radius can be decreased in small steps to 1.25 R_s for 300 m/sec of apoapse velocity changes on a 30-day orbit. A Type B orbit is rapidly perturbed by the oblateness of Saturn resulting in a decreasing radius of ring intersection. For a 30-day orbit, after one year the ring impacts occur at 1.50 R_s. The perturbations can be temporarily offset by small, but critical apoapse impulses. Phase angle coverage is not complete for this orbit but such is the price of a smaller retro propulsion requirement.

The second-generation circular orbiter mission should have the capability of examining the rings at close distance over their full radial extent. This is possible when a nuclear electric propulsion (NEP) system is used for this mission. While performing a spiral orbit capture, the NEP can also be used to maintain a distance of about 10 km above (or below) the ring plane when operation in that plane is hazardous. The instrumentation for this mission will depend on the knowledge gained in earlier ring exploration.

Three launch opportunities were studied for the unconstrained flybys and elliptical orbiters. Launch vehicle and retro propulsion system requirements are given for delivering a 600 lb. Pioneer spacecraft in 1976, 1980 and 1985. The 1976 and 1980 opportunities come before and after the Grand Tour launches and for a launch between these years the illumination of the rings when the spacecraft arrives will be poor. 1985 is the most favorable launch opportunity in its decade. Flybys can be done with a Titan IIID/Centaur/Burner II with a 1000-day flight time. The earth-storable retro propulsion system (I_{sp} = 285) is preferred for Pioneer orbiters and can be used

TABLE S-2 SUMMARY OF CANDIDATE MISSION REQUIREMENTS

CANDIDATE MISSIONS	FLIGHT TIME	LAUNCH VEHICLE	CAPTURE I_{sp}	VHP	NET PAYLOAD
1976 Flyby	980[d]	5+	-	13.8 kps	620 lbs.
1980 Flyby	1040	5	-	13.6	600
with Probe	1240	5	-	11.8	810
1980 Orbiter (A)*	1490	7	385	8.7	590
(B)	1490	7	285	8.7	600
1985 Orbiter (A)	1500	7	285	8.3	630
(B)	1500	5	285	8.3	640
NEP Orbiter#	2100	#	#	0.0	2640

* Orbit A has 2.50 R_s Periapse, 30d Period
Orbit B has 1.25 R_s Periapse, 30d Period

\+ 5 = Titan IIID/Centaur/BII
7 = Titan IIID(7)/Centaur/BII

\# Shuttle/Centaur, P = 100 kw, I_{sp} = 4500 sec., R_p = 1.25 R_s.

if the Titan IIID(7)/Centaur/Burner II is available for the launch. A TOPS spacecraft weighing 1400 lbs is generally beyond the capability of the Titan vehicles, although a flyby or a Type B orbiter could be done in 1985.

For the NEP circular orbiter, the availability of the Space Shuttle was assumed. The payload was estimated to be 2200 lbs. plus 440 lbs. for propellant reserve. This mission needs a power of 100 kw and takes a total of 2000 days. The NEP is launched to earth escape and uses a spiral capture to 1.25 R_s at Saturn.

It is recommended that the Saturn ring exploration begun during Grand Tour be continued with a 1980 launch of a flyby spacecraft with a probe. This can be followed by an elliptical orbiter in the mid-1980's. Eventually the NEP circular orbiter will be needed to complete the exploration program. Because these ring missions use only a fraction of the science payload available, the addition of fields and particles and/or planetology instruments should be studied. The decision on which spacecraft to use, Pioneer or TOPS, should be made on the basis of complete mission studies which also consider the launch vehicle requirements for missions to explore Saturn. An engineering and systems analysis of ring penetration probes is also desired to better define this concept.

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A SURVEY OF CANDIDATE MISSIONS TO EXPLORE SATURN'S RINGS

I. INTRODUCTION

The Saturn ring system is a unique feature in the solar system, its existence demanding exploration to understand its origin and current state. It is also of practical concern to planetary mission analysts; it may constitute a hazard to spacecraft navigating near the planet. While this study investigates mission concepts selected specifically for ring system exploration, the principles established are useful for planning missions to study Saturn and its satellites as well as the rings.

The first study objective is to identify the scientific exploration objectives which characterize the present state of the rings and to relate candidate instruments to the measurement requirements. The next goal is to define and develop candidate mission concepts for ring system exploration. The final objective is to determine what spacecraft, launch vehicles and retro propulsion systems are required to accomplish the desired missions. Major emphasis is placed on the first two objectives since they are unique to this study.

A review of the limited current knowledge, both observational and theoretical, of the rings is presented in Section 2. The review also forms the basis for the selection of exploration objectives. The potential uses of both remote sensing and in-situ techniques are related to the stated objectives and to candidate instruments in Section 3. Following the definition of candidate mission concepts, consideration is given in Section 4 to the selection of flyby trajectories and orbits which have complete phase angle coverage which is needed for the remote sensing measurements. Also discussed are three methods, probe deployment, orbit periapse reduction and orbit perturbation, which result in the ring particle impacts required for in-situ measurements. Then instrument packages are selected and spacecraft (and probe) subsystem implications discussed. Section 5 examines the launch, interplanetary transfer and orbit capture propulsion requirements for each of the candidate missions. The conclusions and recommendations of the study are contained in Section 6.

2. CURRENT SCIENTIFIC KNOWLEDGE OF THE RING SYSTEM

Although the existence of the Saturn ring system has been known for 300 years, our understanding of its basic nature stems from the theoretical paper by Maxwell (1859) on the stability of the system. His results indicated that neither a solid-ring hypothesis nor a liquid-ring hypothesis was tenable, and he suggested that the rings consist of a multitude of individual particles, each one pursuing a separate orbit around the planet. Seeliger (1887, 1893) showed that the liquid-ring hypothesis was invalid because of the reflection properties of the rings. The particle theory was confirmed spectroscopically by Keeler (1895) who observed a Doppler effect, corresponding to differential rotation, in the solar spectrum reflected by the rings. Detailed spectroscopic study of the rings was made by Campbell (1896) who showed that, throughout the system, the orbits of the particles are Keplerian and nearly circular.

2.1 Earth-Based Observations

Until space missions are flown to investigate the nature of the ring system, Earth-based photometric studies must be relied upon to infer its physical properties. Such studies can provide only limited knowledge, using the relatively few types of photometry which can be applied to Saturn's rings. Table I summarizes the possibilities and the information to be gained from each. For subsequent reference, a schematic diagram of the ring system is presented in Figure 1. The three major components of the system, Rings A, B and C, are shown together with Cassini's division. Dimensions of the system are taken from Allen (1963). Earth-based observations are reviewed below in the same order as presented in Table I.

Edge-on Visibility

Observations of the ring system edge-on are possible every 15 years when the Earth passes through the ring plane.

TABLE I

GROUND-BASED PHOTOMETRIC STUDY OF THE SATURN RING SYSTEM

TYPE OF MEASUREMENT	INFORMATION CONTAINED IN DATA
EDGE-ON VISIBILITY	CRUDEST UPPER LIMIT ON VERTICAL RING THICKNESS AND DIAMETER OF RING PARTICLES
STELLAR AND SATELLITE OCCULTATIONS	OPTICAL THICKNESS OF RING AS FUNCTION OF RADIAL AND LONGITUDINAL POSITION IN SYSTEM; DISTRIBUTION OF PARTICLES IN RING PLANE
SURFACE BRIGHTNESS AS FUNCTION OF:	
1. RADIAL AND LONGITUDINAL POSITION IN RING	DISTRIBUTION OF PARTICLES IN RING SYSTEM
2. PHASE ANGLE (SUN-SATURN-EARTH): RANGE $\pm 6°$	PHASE SCATTERING FUNCTION OF RING PARTICLES; MUTUAL SHADOWING BY RING PARTICLES
3. SOLAR ILLUMINATION ANGLE (SATURNICENTRIC DECLINATION OF SUN) RANGE $\pm 27°$	MUTUAL SHADOWING BY RING PARTICLES
POLARIZATION	SCATTERING PHASE FUNCTION OF RING PARTICLES; ALIGNMENT OF PARTICLES IN RING PLANE
SPECTROSCOPIC	COMPOSITION OF RING PARTICLES; SIZE OF PARTICLES IN RELATION TO WAVELENGTH OF INCIDENT RADIATION

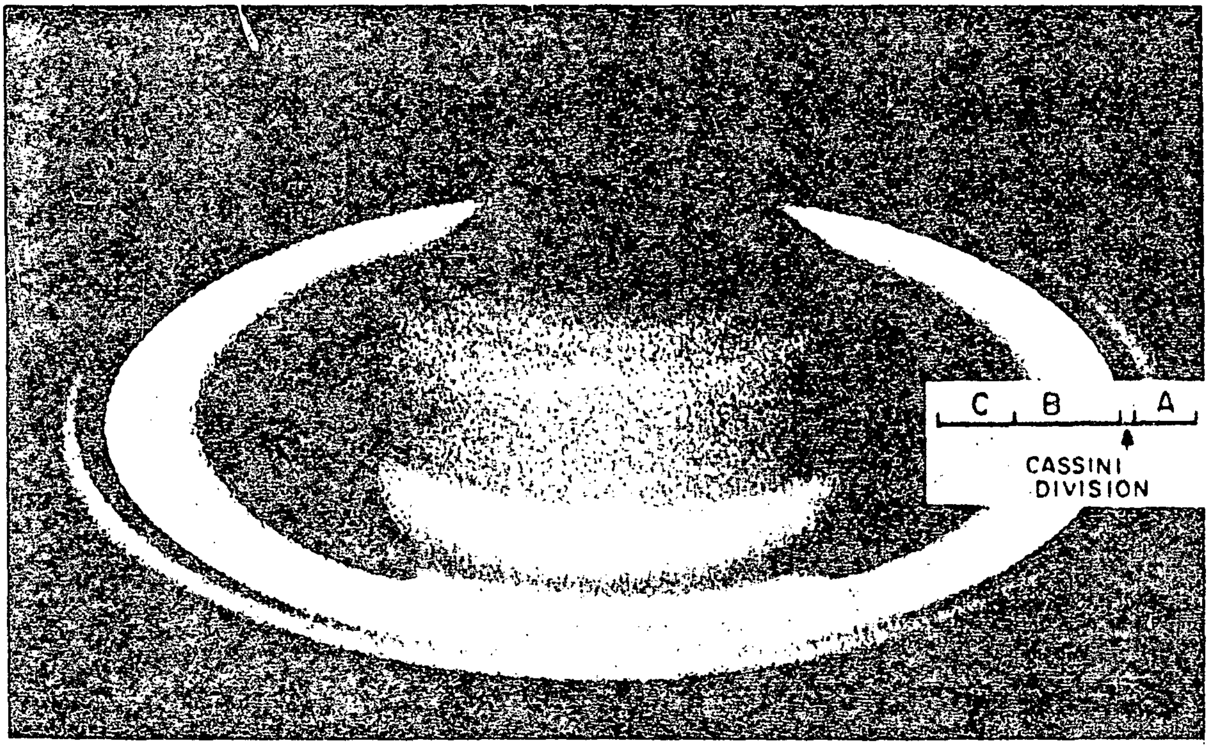

FIGURE I.

DIMENSIONS OF THE SATURN RING SYSTEM

BOUNDARY	RING	DISTANCE
INNER	C	$1.20R_s$*
OUTER	C	1.50
INNER	B	1.50
OUTER	B	1.93
INNER	A	2.00
OUTER	A	2.27

* EQUATORIAL PLANET RADIUS R =60,400KM

During 1966 such observations were carried out worldwide. Typical of the results obtained were those by Kiladze (1967) and by Focas and Dollfus (1969) who derived a ring thickness of 0.9 ± 0.6 kms and 2.8 ± 1.5 kms, respectively. But, in spite of the efforts made to measure the edge-on "visibility" accurately, the interpretation must necessarily be imprecise. These observations provide a crude upper limit to the particle size and the ring thickness. Variations in either property of the rings as a function of radial distance from Saturn are not measured.

Stellar and Satellite Occultations

Observations of the occultations of stars and of an eclipse of the satellite Iapetus by the ring system have shown that all three of its components (Rings A, B and C) are translucent. The available observations of these infrequent phenomena have been reviewed by Cook and Franklin (1958). For Ring B their estimate of the optical thickness was 0.58 which means that $e^{-0.58}$ or 56% of the starlight was transmitted. The optical thicknesses of Rings A and C was less than that of B. Because the original data is qualitative these results are not very accurate. Multicolor photoelectric photometry of a stellar occultation* should be obtained; this quantitative data would be a very valuable input to ring system models.

Cook and Franklin also briefly discussed a study by Bobrov (1952) of the translucency of Ring B which was based on the visibility of the ball of the planet through the ring. While in principle the optical thickness can be estimated in this way, the value of 0.7 obtained by Bobrov is, in the opinion of Franklin and Cook, based on a faulty interpretation.

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* An occultation of an 8th magnitude star by Ring A will occur on 20 April 1972 (J. S. Hall, Private communication).

Surface Brightness

Many observations at visual wavelengths have been made of the variation of the surface brightness of the ring system as a function of radial distance from the planet. Dollfus (1961a) has presented the most detailed and reliable results to date, based on both visual and photographic photometry of the rings. The brightness profile he obtained may be used to study the radial distribution of material throughout the ring system. Recent work by Guerin (1970) shows a very faint feature, which he calls Ring D, between the planet surface and the inner boundary of Ring C.

Measurements of the surface brightness as a function of phase angle have shown the existence of a pronounced phase effect, the rings brightening dramatically near opposition. Franklin and Cook (1965) have determined two color (blue and yellow) phase curves for each of the bright rings, A and B, using photoelectric and photographic photometry. Their photometry is among the most accurate carried out on the ring system to date, and the phase curves they obtained may be considered definitive. Two distinct optical phenomena combine to produce the phase effect, mutual shadowing by the individual ring particles and their characteristic scattering phase functions. Franklin and Cook also attempted to model the rings with their data. But, because the relative contribution of shadowing and scattering could not be established, they were unable to determine which of their models was correct. More data and a more sophisticated method of analysis might produce useful information on the structure of the rings.

Measurements of the variation of the surface brightness of the ring system as a function of solar illumination angle can provide valuable information on the phenomena of mutual shadowing and multiple scattering by the individual particles.

Published data, by Camichel (1958) and Focas and Dollfus (1969), based on photographic photometry only, are meager. Nevertheless Lumme (1970) has used these data to investigate the multiple scattering among the ring particles. He found the maximum optical thickness (of 1.25) was in the B ring.

Polarization

Polarization measurements of the rings made by Lyot (1929) have been reviewed by Dollfus (1961b). More recent data have also been secured by Dollfus. The observed polarizations are small, less than 0.5%, and since recent observations also show that the light from Saturn's disc is more strongly polarized (Hall and Riley, 1969) it is suspected (Hall, 1970) that the ring observations are spurious.

Spectroscopic

Studies by Pilcher et.al.(1970) of the infrared solar spectrum reflected by the ring system have indicated that water-ice is a constituent of the individual particles. Recent high resolution spectrophotometry in the wavelength region 1-5μ, carried out by Kuiper, Cruikshank and Fink (1970 a,b), show strong absorption bands corresponding to those produced by water-ice at the temperature of the ring material. Earlier low resolution studies of absorption features in the wavelength regions near 1μ and 5μ, made by Owen (1965) and Kuiper (1952) respectively, had suggested that ice might be present in the rings. Data on the infrared reflectivity of the rings are not, however, sufficient to determine whether the ring particles are composed entirely of ice, or merely covered by a thin layer of frost.

Recently, Lebofsky, Johnson and McCord (1970) measured the spectral reflectivity of Rings A and B in the wavelength range 0.3 - 1.05μ, and interpreted their results in terms of compositional implications for the ring material. They found that the reflectivity decreases sharply towards blue and ultraviolet wavelengths, in the same manner for both rings. On the expectation that a pure water frost would have a flat reflection spectrum in the visual region, Lebofsky, et. al. suggest that the ring particles must be composed of material other than pure ice, perhaps frost covered silicates. Their interpretation is not definitive since it did not consider the influence of particle-size on spectral reflectivity.

2.2 Saturn Ring System Models

In a thorough rediscussion of Maxwell's classic paper, Cook and Franklin (1964, 1966) derived limits on the volume density of the ring which are based on stability of the ring system. Densities greater than 1.04 g/cm^3 are excluded because the rings would be unstable. Stability was assured if the density was 0.18 g/cm^3 or less. This work has been extended (Franklin and Colombo, 1970; Franklin, et. al., 1971) by using the observed radial structure of the rings to determine model parameters. The position of the Cassini division, which is displaced from the prediction based on the resonance associated with 1/2 Minas' period, is matched with observation if the volume density is 0.1 g/cm^3 or more. The model used has particles of uniform radius in a single layer. An average particle separation of 200m and average particle diameters of 100 to 150m are found for the most dense part of Ring B - this ring model has also been used to predict a division in the rings between Ring C and the faint ring of Guerin (1970) and the possible existence of two narrow rings outside Ring A. If these are substantiated the radial extent of the rings will be terminated at about 2.70 R_s. Current dynamical models do not explain how the rings can stay in the equatorial plane while Saturn's pole precesses with a 2.5 million year period.

Franklin and Cook (1965) analyzed the data they reduced on the ring brightness as function of phase angle using models including mutual shadowing and the glory phemonenon, the pronounced brightening at 0° phase angle. Their Model I which gave better agreement with observation consisted of a ring of unknown thickness and particles of unknown radius with surface irregularities of 7μ typical size. Model II, composed of particles with radii of about 300μm in a ring 3 to 10 cm thick, could not be excluded because of limited data and an incomplete description of the processes contributing to the phase effect.

A very different result has been found by Price (1971). Mie (1908) scattering theory for small ice spheres was used to derive the photometric properties of the rings. The best photometric data available was analyzed to obtain an optically self-consistent ring model containing ice crystals of 0.1μ average radius. To derive a particle size distribution for this model, more spectral reflectivity data as a function of phase angle is required.

There is a large variation in particle sizes between these models, from 10^{-7} to 100 m. One explanation is that ring particles like many other substances have a brightening at zero degrees phase angle as a result of small scale roughness on a large body. Some inferences on particle size can be made by considering evolutionary processes at work on the rings. The effects of sputtering by ultraviolet radiation and proton bombardment erode material at a rate of approximately one centimeter per billion years (Harrison and Schoen, 1967). Thermal evaporation of ice, however, is relatively insignificant (Owen, 1965). Meteoroid bombardment has been studied by Cook and Franklin (1970) and by Banderman and Wolstencroft (1969) who suggest that the rings have been altered by collisions between meteoroids and ring particles. Particle-particle collisions should also result in surface erosion. Such impacts will occur if the ring particles have an average radius less than 100m (Franklin and Columbo, 1970). An evolutionary study of the ring system, including all these disruptive processes plus any accretion from meteoroid bombardment, to determine if the ring system is in equilibrium has not been done.

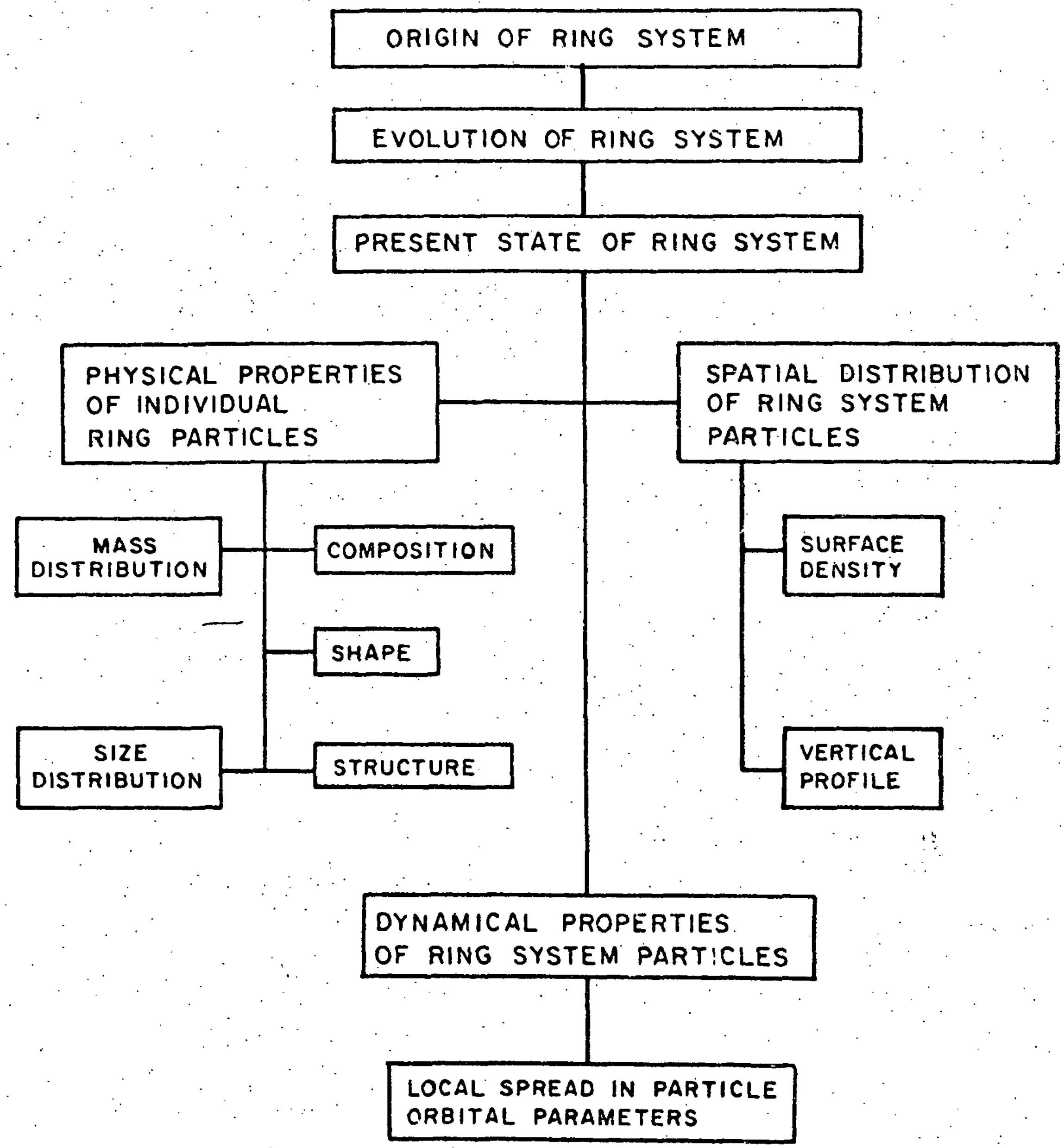
In general theoretical studies of the rings are inconclusive because the data is incomplete and because the studies are restricted in scope. The first problem can be corrected with missions to study the ring system. Not only will the existing data be more complete, but new types of data can be provided.

2.3 Scientific Objectives

The overall objective of Saturn ring system exploration is to determine the origin of this feature and to be able to understand its evolution. If progress is to be made toward this goal, a complete understanding of the current state of the ring system is essential. As shown in Figure 2, the present state can be divided into three areas: the properties of individual particles, the spatial distribution of material, and the dynamical properties.

Each area can be subdivided into specific objectives. For example the particle physical properties consist of a size distribution, a mass distribution, composition, shape and structure. The size distribution can be expressed as the fraction of particles whose radius is greater than a given size. The mass of a particle is related to its size and density. Observationally, however, these two distributions are independent. The size distribution and the shapes and structure of particles should be sensitive to evolutionary processes. The composition, on the other hand, should provide a clue to the

FIGURE 2. SCIENTIFIC OBJECTIVES OF SATURN RING EXPLORATION



origin of the rings. Specifically, a meteoritic composition might imply accretion as the formative process. A predominance of ice might result from the disruption of a liquid ring soon after planetary formation. A comparison with the composition of Saturn's satellites should be made since the rings could be the result of the breakup of a satellite. From certain isotopic abundances, an age for the particles can be defined, but its usefulness depends on understanding the evolutionary process. All of these physical properties should be studied at many locations in the rings.

The spatial distribution has been divided into two parts: The surface density and the vertical profile. The former is simply the fraction of the area occupied by particles. It may also be expressed as the number or mass of particles in a vertical column of unit area. Radial variation in the surface density is expected, but longitudinal variations are also allowed. The vertical profile is the distribution of particles away from the equatorial plane. It is much easier to determine the surface density and for some purposes this data is sufficient. The dynamical properties of the ring system are described by the local variation in particle orbit parameters, especially the eccentricity and inclination. The spatial distribution and the spread in orbital parameters are both needed to determine the probability of particle-particle collisions which are an important evolutionary process.

Another interesting problem is formulating an engineering environmental model for the rings. The most important measurables are the mass distribution and the surface density. The meteoroid protection problem can then be assessed. The design of advanced spacecraft and instruments may require inclusion of other measurables, especially the vertical profile and local spread in orbital parameters, in the engineering model.

3. MEASUREMENT TECHNIQUES AND INSTRUMENTS

In this section, measurement techniques are discussed and related to the specific scientific objectives already defined. This pairing of objectives and techniques is summarized in Figure 3. A technique was judged useful if the information returned was directly related to the measurable. Where the information provided is indirect and possibly ambiguous the technique was labeled somewhat useful. The first half of this section treats remote sensing techniques which measure the reflection and emission of electromagnetic waves from the particles. The second part looks at in-situ measurements which involve contact between the instrument and the particle. Candidate instruments are proposed based on qualitative analyses and experience. Conceptual instrument designs starting with a set of measurement specifications are beyond the scope of this study.

Typically first generation missions observe the rings from a distance of 0.1 to 10 planet radii and have high velocity impacts (~ 20 km/sec) with ring particles. The characteristics of the second generation circular orbiter mission are a low relative velocity and small distances ($<$ 10 km) between the spacecraft and the rings. When discussing techniques and instruments, it is also necessary to keep in mind the wide range (0.1 μm to 100 m or more) of particle sizes that may be encountered in the rings.

3.1 Remote Sensing Techniques

3.1.1 Visual Imagery

Visual imagery is a very powerful technique for study of planets, since it achieves high spatial resolution and has time resolution as well. For the exploration of Saturn's rings the spatial resolution feature can be used to get the radial distribution (or surface density) of particles. This can and should

FIGURE 3. MEASUREMENT TECHNIQUES FOR SATURN RING EXPLORATION

MEASUREMENT TECHNIQUES / RING SYSTEM PROPERTIES	REMOTE SENSING						IN-SITU		
	VISUAL IMAGERY	PHOTOPOLARIMETRY	RADIOMETRY	SPECTROSCOPY	RADIO OCCULTATION	RADAR/LASER	METEOROID DETECTION	MASS SPECTROSCOPY	SAMPLE ANALYSIS
MASS DISTRIBUTION	O	O	O		O	O	X		X
SIZE DISTRIBUTION	X	X	X		X	X	O		X
COMPOSITION		O	O	X	O	O	O	X	X
SHAPE	X	O			O	X			X
STRUCTURE	X	O	O		O	X	O		X
ORBITAL PARAMETERS	X					X	O		
SURFACE DENSITY	X	X	X		X	X	X		
VERTICAL PROFILE	X					X	X		

X = USEFUL TECHNIQUE O = SOMEWHAT USEFUL be done at great distances from the rings so that large portions of the ring system can be included in a given image. Higher resolution would be useful for the study of features in the ring particle distribution such as the Cassini and Encke divisions, but detection of individual particles is difficult.

A possible first generation instrument is the TOPS silicon intensifier vidicon camera with a resolution of 10 μ rad or 60 m at 0.1 R_s. For a TV which is on a spacecraft targeted to intersect the rings, image smear limits the resolution which can be obtained. For typical impact velocities (10 to 20 km/sec) resolutions between 10 cm and 10 m may be obtained depending on the sensor type and the lens aperture used. However, if there are appreciable numbers of such particles, the spacecraft should not be entering such a hazardous region.

With a circular orbiter smear will not be a problem so the resolution will be 10 cm at 10 km. With this performance the size distribution, particle shapes and structure can be measured for particles larger than say 30 cm. It should also be possible to determine orbital elements for particles which can be followed for a period of time.

If no individual particles are seen at a distance of 10 km, then the distance between the spacecraft and the rings can probably be safely reduced to study smaller particles. Should the particles be very tiny, then examination of a sample collected on a specially prepared surface would be illuminating.

3.1.2 Photopolarimetry

Photopolarimetry may very well be the most useful remote sensing technique available for the study of Saturn's rings during first generation missions. Present evidence indicates that the ring particles may have radii on the order of the wavelength of solar radiation. If so, their scattering and extinction properties will depend rather sensitively on their physical properties. Photopolarimetry can provide valuable information not only on the particle size distribution but also on the surface density of the ring system; it will also provide preliminary information on the shape and composition of the ring particles. At worst, photopolarimetry will indicate whether or not the radii are of the same order as the wavelength of the incident radiation.

Because photometry deals directly with the first order effects of the scattering of light by small particles, it is more useful for defining the basic structure of the ring system than polarimetry which deals in second order effects. Although polarimetry should not be dismissed too lightly, in this brief survey of ring missions, it will not be possible to discuss both. Either of two types of photometry can be used towards achieving the mission objectives. They are, 1) measurement of the surface brightness of the ring system as a function of phase angle, and 2) the measurement of the extinction of direct sunlight during solar occultation.

Multi-wavelength photometry of the surface brightness of the ring system as a function of phase angle (Sun-ring-spacecraft) can provide much information on the size distribution of the ring particles. To illustrate the variation of the phase effect with changing particle size, a calculation of the theoretical phase curves for an idealized model of the ring system will be made. It is assumed that the surface density is low (< 1) and uniform, and that the ring particles are clear, non-absorbing ice spheres of uniform but arbitrary radius. For optical wavelengths the refractive index of the ice particles may be taken as 1.31. We will define a size parameter, x, such that

$$x = \frac{2\pi a}{\lambda} \qquad (1)$$

where a is the radius of the particle, and λ is the wavelength of the incident radiation. We will assume further that multiple scattering and mutual shadowing among the ring particles are both negligible. In the basis of our assumptions, the Mie theory of scattering can be used directly in the computations.

Following Price (1971), the surface brightness of the ring system is proportional to the product $g \cdot K_{sca} \cdot S$, where g is the "gain" of an individual scatterer, K_{sca} is the scattering efficiency of an individual particle, and S is the surface density of the ring system. The "gain" (g) is a strong function of phase angle (α); it is defined by

$$g = \frac{\text{Intensity of radiation scattered toward spacecraft}}{\text{Intensity if radiation were isotropically scattered}} \quad . \quad (2)$$

In the special case where the phase angle is zero, we have

$$g_o = \frac{K_b}{K_{sca}}$$

where K_b is the back-scattering efficiency of the particle, defined as the ratio of its "radar" cross-section to its geometrical cross-section. K_{sca} is defined as the ratio of the isotropic-scattering cross-section to the geometrical cross-section. Calculations of $g\ K_{sca}$ were carried out over the entire range in phase angle ($0 < \alpha < 180°$) for selected particle sizes in the range $0.1 < x < 10$. The main results are plotted in Figure 4. For comparison, the phase curve for very large particles, with white, non-absorbing, perfectly diffusing surfaces, is also plotted. The size parameter x may be translated into particle radius using equation (1); for $\lambda = 0.55\mu$, the radiation unit size parameter corresponds to a 0.1μ particle radius.

FOLDOUT FRAME

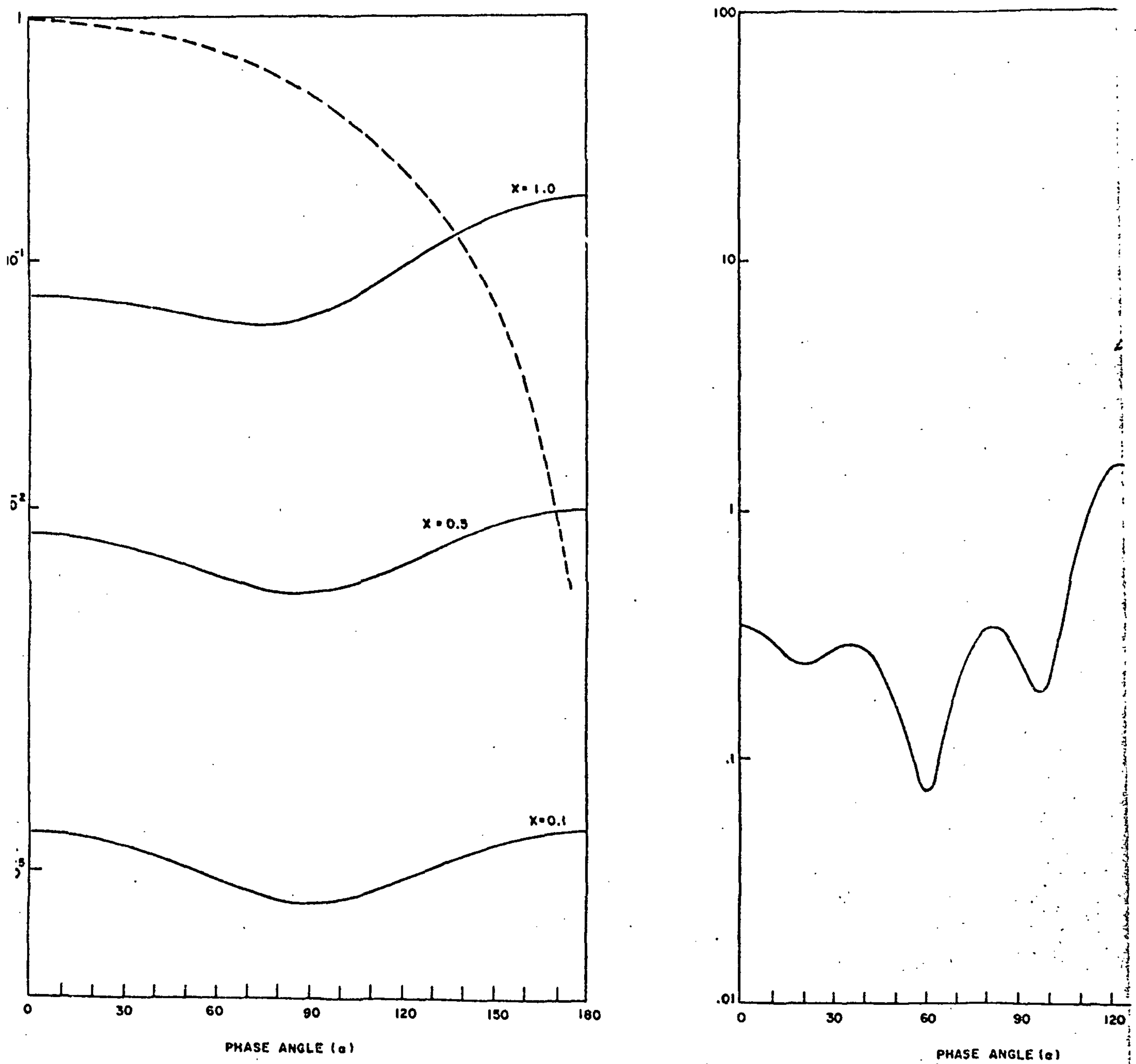
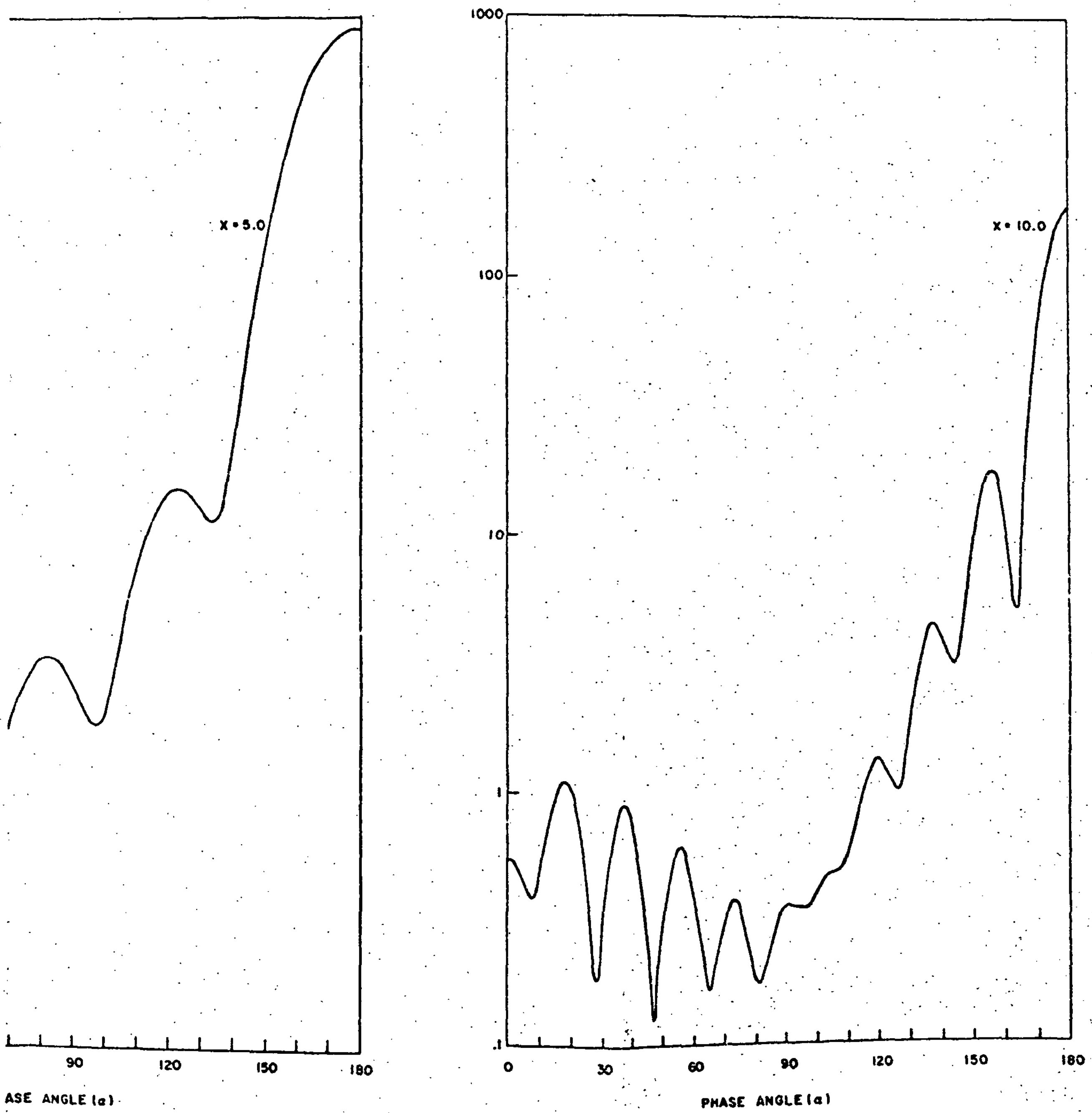


FIGURE 4. THE GAIN-SCATTERING PRODUCT AS A FUN

——— CLEAR, NON-ABSORBING ICE SPHERES

- - - - WHITE, NON-ABSORBING, PERFECTLY D

FOLDOUT FRAME 2



PRODUCT AS A FUNCTION OF PHASE ANGLE

BSORBING ICE SPHERES

BSORBING, PERFECTLY DIFFUSING SURFACE

Figure 4 indicates that, the phase curve for particles of uniform size is strongly dependent on particle size. For $x < 1.0$ the shape of $g\ K_{sca}$ vs. α is about the same but the absolute value decreases for smaller values of x. However as x becomes greater than unity the gain scattering product has many more oscillations and has a pronounced peak at 180°, the forward scattering point. In fact, multi-color photometry of the ring system as a function of phase angle can be used to infer the characteristic size and size distribution of the ring particles. Information can also be obtained on the surface density of the ring system. Difficulties in reconciling theory with observation can be resolved by using either spheres of non-uniform radius or non-spherical particles.

During solar occultation the brightness of the sun will be reduced by the factor $K_{ex} \cdot S \cdot \csc\theta$, if multiple scattering is negligible. K_{ex} is the extinction efficiency of an individual particle, defined as the ratio of the extinction cross-section to the geometrical cross-section. S is again the surface density of the ring system and θ is the angle between the ring plane and the spacecraft-sun line. In order to illustrate the effect of particle size on the extinction, K_{ex} was calculated as a function of the size parameter x in the range $0.1 < x < 20$, using the same assumptions as before and the Mie theory. The results in Figure 5 show that if the characteristic size parameter of the ring particles is small ($x \lesssim 5$), extinction measurements can be used to infer, without ambiguity, the particle size. Measurements at more than one wavelength are required to obtain information on both the size distribution of the ring particle, and the surface density of the ring system. If the particles are larger ($x \gtrsim 5$), a unique determination of their characteristic size is not possible; only a lower limit can then be obtained. By comparison with photometry of the surface brightness of the ring system as a function of phase angle, solar occultation extinction

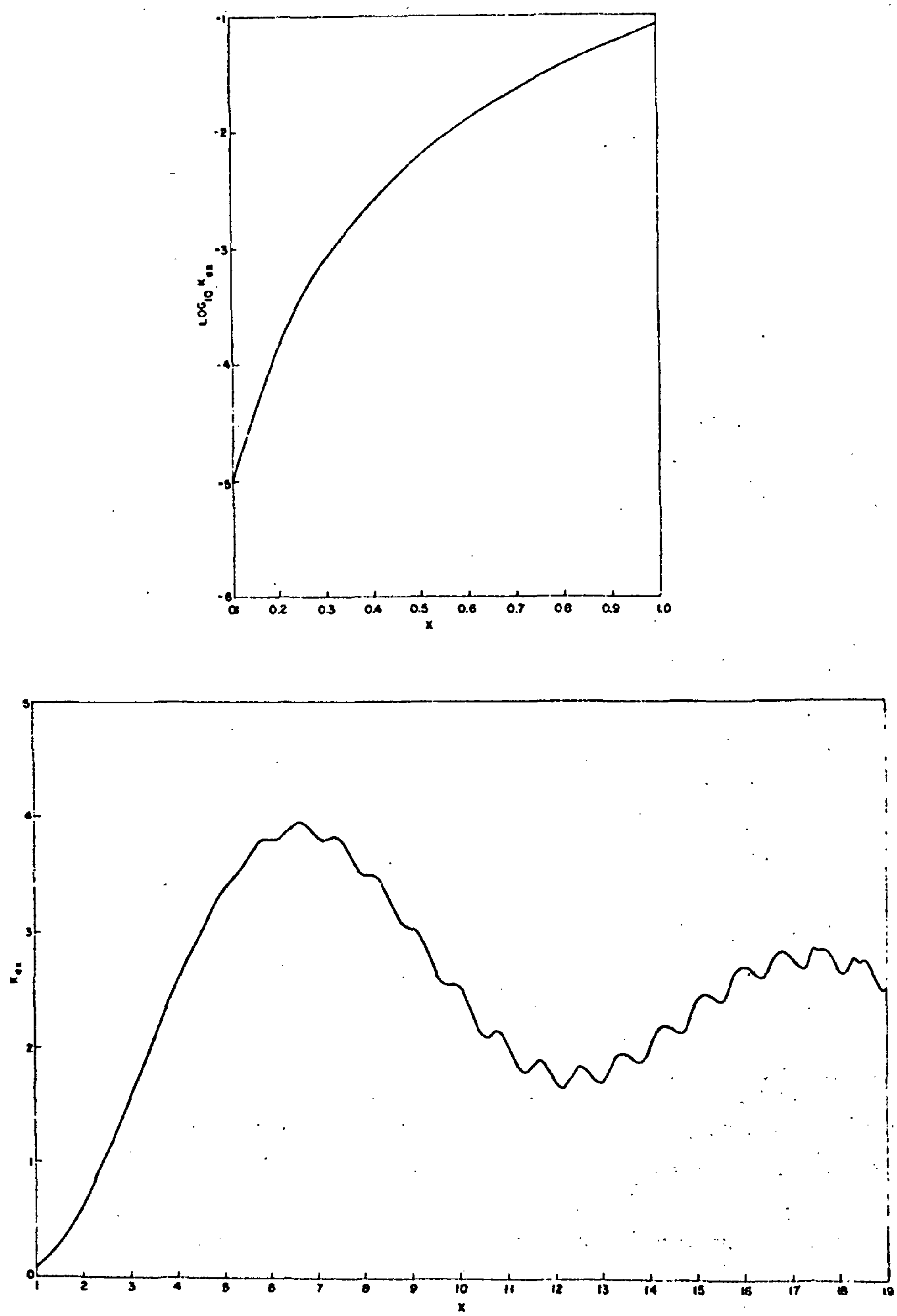


FIGURE 5. MIE SCATTERING FOR DIELECTRIC SPHERES OF REFRACTIVE INDEX 1.31:
EXTINCTION EFFICIENCY, K_{EX} , V SIZE PARAMETER, X.

measurements are therefore less useful for defining the size distribution of the ring particles.

Effective application of these photometric techniques requires that the interpretation of the observational data be unambiguous. Thus it will be essential that the observations be compared with much more sophisticated models for the scattering of electromagnetic waves by the rings. In particular, the assumptions used here of clear, non-absorbing, ice spheres of uniform radius must be relaxed to include absorption (especially at infrared and radio wavelengths), non-spherical shapes and size distributions. In addition the processes of multiple scattering and mutual shadowing are important for many illumination and phase angles. The idealized case was studied because any changes would have greatly increased the complexity and cost of the computation.

For the photometry/polarimetry measurements the Pioneer F/G instrument appears adequate. It is specifically designed for accurate visual photometry (in red and blue light) and polarimetry. With a 1 mrad field of view it can achieve 100 km or better resolution when the spacecraft is within a planet radius of the rings. A wide range in wavelength should be used since size information is contained in the scattering properties observed at different size parameters. Thus the addition of a few more colors, especially in the near UV and near IR, would be useful. The location of the instrument on the spacecraft must be chosen carefully to get the full phase angle coverage.

3.1.3 Radiometry

The study of the infrared thermal emission from the rings is a valuable technique. From the ratio of the observed flux to that from a black body at the same temperature the surface density can be deduced. In addition temperatures should be measured because the ring particles are typically in eclipse for part of their orbits about Saturn. At 1.2 R_s, the eclipse can last for about 1.5 hours of the 5 hour period, while at 2.27 R_s the orbit period is 14 hours and the eclipse 2 hours or less. The rate of cooling and subsequent heating should yield clues to particle size and thermal conductivity. If it is assumed that the rings have longitudinal homogeneity, then the eclipse data are contained in a temperature map of the rings. Otherwise it is necessary to measure the temperature of a given location in the ring as a function of time. Another potential observation is the extinction of thermal emission from Saturn measured through the rings. Both the eclipse and extinction observations are best done at a variety of wavelengths from 10μ to 1.0 mm, a range that is intermediate between photometry and radio occultation.

For the thermal inertia measurement and to measure the extinction of Saturn thermal energy a simple two or three channel radiometer is called for. A 10 mrad FOV, similar to the Pioneer F/G instrument, could be used. The expected 70°K temperature of the ring particles might make it desirable to extend the measurements to longer wavelengths than the current 60μ. A modest increase in sensitivity with either larger optics or a longer integration time is required for the surface density measurements. Neither change would be difficult.

3.1.4 Spectroscopy

While spectroscopy can be useful for determining the composition of the rings, in-situ measurements are preferred. Reflection spectroscopy in the near infrared has shown that water ice is a major constituent. At 1% spectral resolution these studies may also indicate the petrology of any rocky component of the ring particles. Absorption spectroscopy (i.e., looking at the sun through the rings) will reveal the presence of gases and metallic vapors associated with the rings. Based on the Mariner instruments, it is expected that the spectrometer would weigh at least 10 kg.

3.1.5 Radio Occultation

If the radio transmissions from the spacecraft pass through the rings on their way to the earth then the amplitude of the received signal may be used to infer the size distribution and surface density of particles of centimeter size and larger. If the extinction (or attenuation) of the radio signal is small, then particles of centimeter size are rare. Large fluctuations in the signal would indicate the presence of particles whose size is at least the same as the geometrical beamwidth which is typically many wavelengths across. A dual band spacecraft transmitter, X-band (3 cm.) and S-band (10 cm), is preferred.

For the surface density determination, it is desirable to have the occultations occur over the full radial extent of the rings. As with the photometric studies, it is also helpful to have an intercept angle (about the same as solar illumination angle) that is large to minimize multiple scattering and shadowing. However, if the frequency of centimeter particles is low, then small angles could take advantage of longer pathlengths. Since in the theoretical calculations of extinction assumptions are made about the composition, shape and structure of the particles, the observations will yield some data about these measurables as well.

3.1.6 Radar/Laser

In addition to the passive remote sensing techniques considered above, valuable information can be obtained with an active system. Either a radar, typical wavelengths from 1.0 mm to 10 cm, or a laser operating in the 0.5μ to 10μ range could be used. Such devices are most useful when the spacecraft-particle distance is small so that the properties of individual particles can be determined. The amplitude of the return signal from a particle contains size, shape and structure information. The time delay and Doppler shift in frequency specify the range and relative velocity of the particle which can be converted into its orbital elements. For most of these measurements the particles must be much larger than wavelength of the radar or laser.

Since the radar or laser is intended only for the second generation circular orbiter, its design will depend on the first generation data. A lower limit of 20 kg has been estimated for the weight of this instrument. It would not appear useful to raise the power of either a radar or laser to get backscatter from particles with dimensions smaller than the wavelength. The laser detector will, of course, require a narrow band filter to exclude reflected sunlight.

3.2 In-Situ Techniques

In this section instruments involving physical contact between the particles and the device are discussed. The first two techniques of meteoroid detection and mass spectroscopy can be employed when the particles impact at high velocities while the sample analysis methods are better suited to low relative velocities. It must be recognized that one mission can have ring impacts at only a few locations and that impacts may be too hazardous for early missions. Thus in-situ measurements are complimentary to and should not replace remote sensing measurements.

3.2.1 Meteoroid Detection

Instruments that detect micrometeorite impacts are very useful for determining the mass distribution, the surface density and the vertical profile. Note that this technique is sensitive to mass, not size, because the measured quantities are momentum, kinetic energy, etc., which involve mass rather than a scattering cross-section. To measure the surface density the rings must be intersected at many radial distances and to get the vertical profile the detector must have good time resolution. The particle composition and structure can affect impact characteristics, but are secondary to mass and velocity.

With high impact velocities characteristic of first generation missions it probably is impossible to measure the orbital elements of particles with meteoroid detectors to the accuracy desired. It also appears that the Sisyphus (or optical) detector will not work because single particles cannot be resolved.

At the 10 to 20 km/sec typical impact velocities, current technology impact sensors should function well. Some candidates are pressurized cells such as those on Pioneer F/G and the impact ionization detector which is on Pioneer 8. The time-of-flight feature of the Pioneer 8 instrument is not required since the magnitude and direction of the particles relative to the spacecraft will be known. However, because the rings are about one kilometer thick, the good time resolution will be important if the vertical profile is to be measured. The impact mass spectrometer function could be added to the impact ionization detector, forming a new instrument but one which can be built. Pressure cells are one shot devices more appropriate to a mission which makes one pass through the rings while the impact mass spectrometer is preferred for the orbiters.

3.2.2 Mass Spectrometry

The objective for mass spectroscopy is to determine the elemental and molecular composition of ring particles in the 1-60 amu mass range. The elements from hydrogen to iron and molecules from H_2 to sulfur bearing radicals such as OCS are included in this mass interval. For first generation missions, the high velocity impact will ionize the particles. The ionized atoms can then be analyzed in a time-of-flight mass spectrometer similar to that planned for HELIOS. For second generation missions, mass spectrometry can be performed on a collected sample by using an ion beam to ionize the material. Vaporized molecules can also be ionized by radio frequency excitation or electron beams.

3.2.3 Sample Analysis

The obvious prerequisite for sample analysis is sample collection. Therefore a brief discussion of collection methods preceeds the description of sample analysis techniques to be used on a second generation mission with a circular orbit.

For small particles (up to millimeter size) a "flytrap" can be used to collect particles on a specially prepared surface. For medium sized particles (up to one meter size) rendezvous and a sample handling device would be useful. For large rotating particles, rendezvous and docking (i.e., anchoring the spacecraft to the object) are required. For larger size objects a drill or other method of sampling the interior of the particle would be useful in a search for inhomogeneities.

Two measurement techniques, visual imagery and mass spectroscopy, previously discussed can be employed with collected samples of all sizes. For composition measurements the possibilities are numerous, including mass spectroscopy, alpha and proton backscattering, neutron activation,wet chemical analysis and x-ray spectroscopy. The last technique can also provide valuable data on the mineralogy. The structure of larger particles can be tested directly by applying pressures with the sample handling or collecting device. The design and selection of instruments for in-situ sample analysis must be based on a better model for the rings formulated with data returned by first generation ring missions.

4. MISSION ANALYSIS AND SYNTHESIS

Five mission concepts for Saturn ring system exploration are proposed and defined at the beginning of this section. These concepts are developed by studying the phase angle coverage problem for remote sensing measurements and the ring impact situation for the in-situ techniques. Science instrument packages are selected for each concept and the implications of that package on the TOPS and Pioneer spacecraft will be considered.

4.1 Mission Concepts

The constrained flyby is the first mission concept. The best example is the 1977 Jupiter-Saturn-Pluto mission; the swingby to Pluto is the constraint . For this mission and for the 1978 JSUN too, the restriction limits the phase angle coverage and thus adversely affects remote sensing measurements. The choice of arrival date is also restricted to a time interval during which the rings are poorly illuminated; i.e., the declination of the sun is small ($\delta_{\odot} < 12°$). These Grand Tour missions use the TOPS spacecraft which has a large science instrument payload (60 kg) and is three-axis stabilized for accurate pointing.

The next concept is the unconstrained flyby whose targeting at Saturn is to be optimized for remote sensing of the rings. The 1976 and 1980 opportunities were studied since they bracket the Grand Tour launches. Any mission launched in the 1980's will arrive when the rings are open and thus well illuminated ($\delta_{\odot} > 16°$). In Section 5 it is shown that in any year a Pioneer, but not always a TOPS, spacecraft can be delivered ballistically when a Titan vehicle is used for the launch.

A first generation orbiter mission can explore the rings from a long period inclined elliptical orbit. Two choices for

TABLE 2 SATURN RING MISSION CONCEPTS

MISSION CONCEPT	EXPLORATION POTENTIAL	S/C TYPE	OPPORTUNITIES STUDIED	δ_o *
1. Constrained	Limited Remote Sensing	TOPS	1977 JSP 1978 JSUN	3.7 11.3
2. Unconstrained Flyby	Good Remote Sensing	Pioneer	1976 Direct 1980 Direct	-5.8 16.4
3. Elliptical Orbiter	Good In-situ and Remote Sensing	Pioneer	1980 Direct 1985 Direct	20.1 26.2
4. Circular Orbiter	Excellent In-situ and Remote Sensing	New	NEP (Any Year)	-
5. Deployed Probe	Engineering Data	TOPS Pioneer	1977 JSP 1980 Direct	3.7 17.5

* Declination of the Sun on the Nominal Arrival Date (Degrees).

the orbit orientation will be discussed; one has excellent phase angle coverage and can perform radial in-situ measurements if the periapse is lowered while the other has a less extensive phase angle range but requires much less propulsion for the in-situ measurements. Again the results of Section 5 show that in both 1980 and 1985 a Pioneer spacecraft can be placed in orbit.

All three of the above concepts can be characterized by ring observation distances of 0.1 to 10 planet radii and high velocities with respect to the ring particles (10-20 km/sec). It follows that the most useful remote sensing techniques will be photopolarimetry, radiometry and occultations. In-situ data is obtained with an impact mass spectrometer to be included on the elliptical orbiters. For the fourth concept, however, the spacecraft-particle distance will be 10 km or less and the relative velocity low so that the TV and radar/laser should be important techniques with this second generation equatorial circular orbiter, in-situ sample analysis is also possible. Radial exploration of the ring system is accomplished during a spiral orbit capture with low thrust nuclear electric propulsion (NEP). NEP is also used for the interplanetary transfer.

The last concept is a probe which can be deployed from a flyby spacecraft and targeted for ring impact. Using occultation and meteoroid detection as measurement techniques, such a probe could obtain the two ring system properties (mass distribution and surface density) needed for an engineering model. This is also the only way to obtain in-situ measurements if the ring environment is either unknown or known to be hazardous to a spacecraft.

4.2 Phase Angle Coverage

One of the important requirements for the photometry/polarimetry technique is complete phase angle coverage. Earth-based telescopes study only 0 - 6° but it is desirable to obtain all 180 degrees. A mission will have complete phase angle coverage if backscatter (or 0°) and solar extinction or occultation (180°) data are obtained over the full radial extent of the ring system (1.20 to 2.27 R_s). The locus of points on the rings where both measurements can be made is determined by finding the intersection of the sun-spacecraft line (or its extension) with the ring plane. When the rings lie between the spacecraft and the sun, extinction data is obtained. The backscatter measurements are available when the extension of the sun-spacecraft line intersects the rings. It will be assumed that the instruments can and will be pointed to the desired ring locations.

Results of such calculations are presented in Figures 6, 8, 9 and 10. Each figure shows the rings and Saturn in equatoral projection. The area of the rings in shadow was found using the declination of the sun on the arrival date. The locus of the intersection is shown as a dashed line. The portions of that line which are useful for backscatter and extinction observations are designated by the symbols "0" and "180°" respectively. A solid line marks the projection of the spacecraft's path on the equatorial plane. The node (Ω) and periapse (P) of the spacecraft are shown. The distance from the spacecraft path to the observed point is indicated by a dot-dash line. The locus for earth occultations was not calculated but should be close to the location of solar occultations.

The planned Outer Planets mission to Saturn, the 1977 JSP*, has neither 0 nor 180° phase angle coverage, so no figure has been included. The poor coverage results from the large periapse radius of almost 10 R_s and the low solar illumination angle (3.7°). In fact the spacecraft and the sun are on opposite sides of the ring plane for almost the whole encounter. Figure 6 shows the phase angle coverage for the 1978 JSUN Grand Tour mission with

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* Planetocentric orbital elements for the Outer Planets missions were provided by P. Penzo of Jet Propulsion Laboratory.

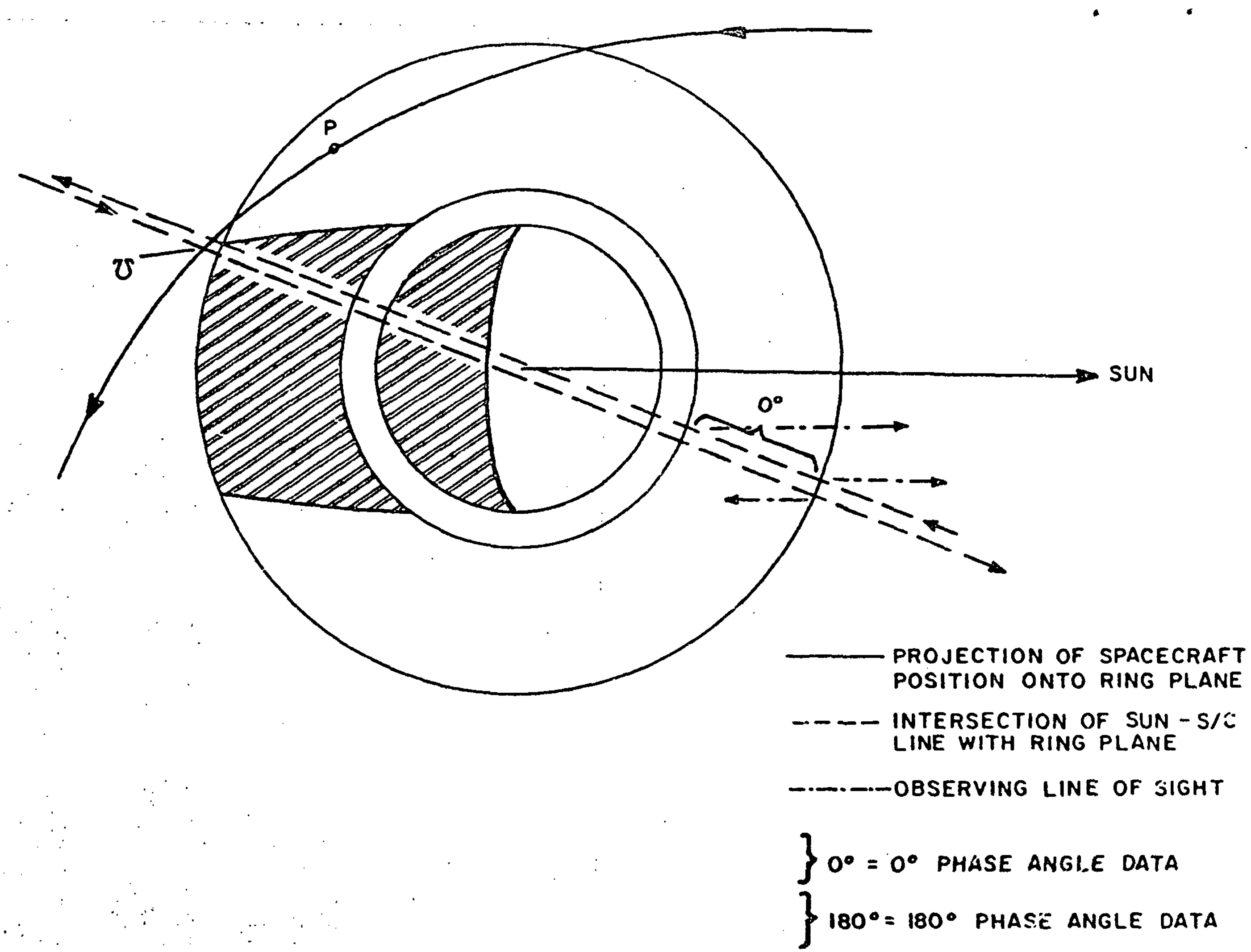

FIGURE 6. PHASE ANGLE COVERAGE FOR 1978 JSUN.

an exterior ring passage at Saturn. Backscatter data can be obtained at about 20 hours before periapse but the disc of the planet is behind the rings. Other opportunities for backscatter and occultation measurements (as evidenced by three other locations where the dashed line crosses the rings) are useless because the planet blocks the path.

For unconstrained flybys and elliptical orbiters three types of trajectories (or orbits) have been identified which give good to excellent phase angle coverage. The best coverage is obtained by a spacecraft path in the eccliptic plane. Thus the inclination of the orbit (Type A) will be the same as the declination of the sun ($\delta_{\odot}$), the node is about 90° from the right ascension of the sun and the argument of periapse (ω) is approximately zero (see Figure 7a). The nominal periapse is 2.50 R_s. Typical phase angle coverage is shown in Figure 8. Two complete radial scans of both backscatter and extinction data are obtained during each orbit. However, if the declination of the approach asymptote (δ_{VHP}) is greater than $\delta_{\odot}$ then this trajectory plane is not available.

The second candidate orbit (Type B) has a low periapse which requires that the argument of periapse be 90° so that the ring plane is intersected outside the ring system. Periapse radii of 1.10 R_s for flybys and 1.25 R_s for orbiters have been used. The rings are intersected at about 2.45 R_s in both cases. As Figure 7b shows the node is typically near the solar direction. The inclination is only slightly larger than the approach declination. Between the node and periapse of this orbit the rings can be examined at close distance, often within 0.1 R_s. This Type B trajectory gives ring occultations at smaller spacecraft - 180° point distances, less than 0.5 R_s in the case illustrated in Figure 9. However, if $\delta_{VHP} > \delta_{\odot}$ then this orbit gives backscatter instead of extinction data. The Type B orbit never gives a full radial scan of the ring system at both 0 and 180°.

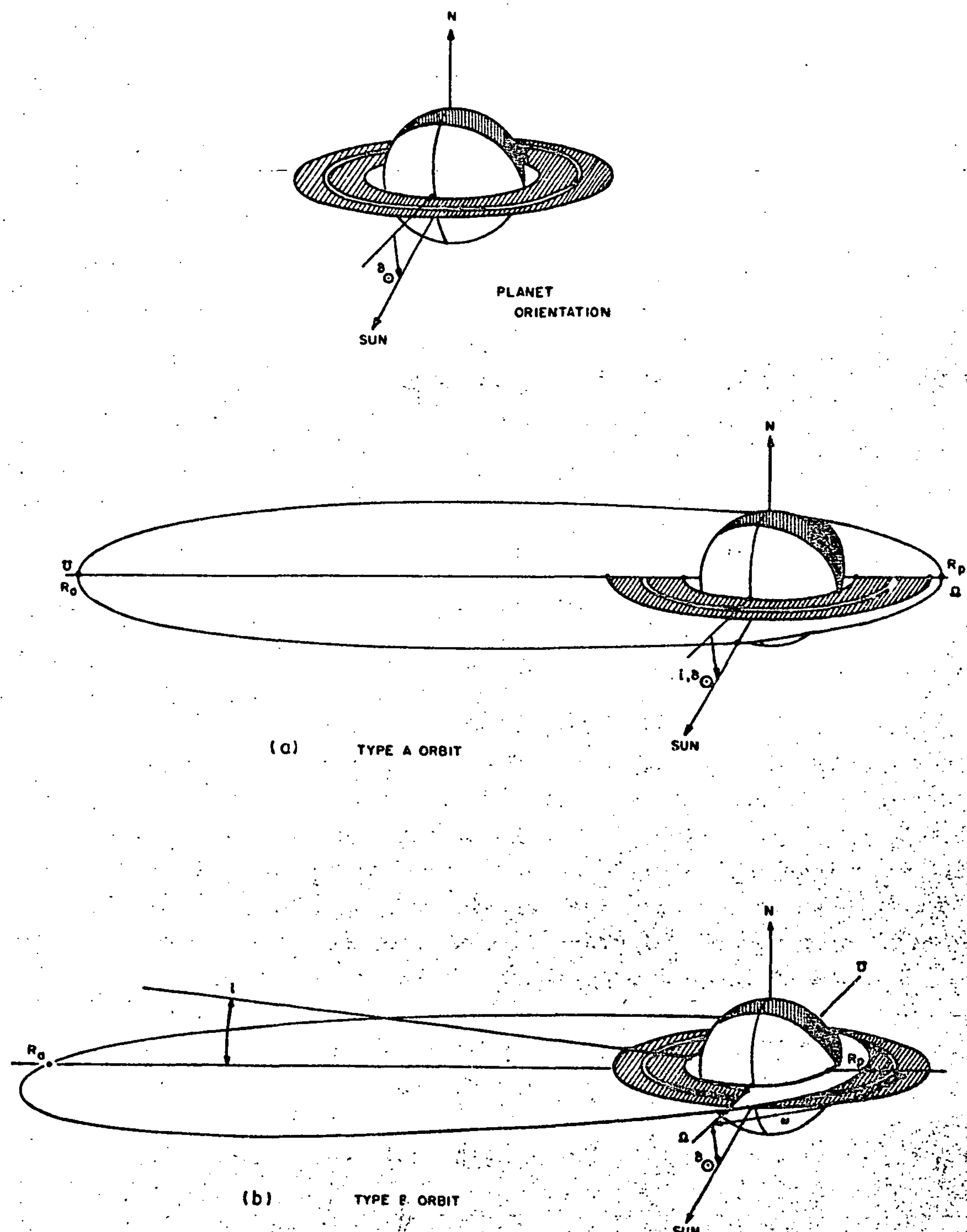

FIGURE 7. ORIENTATION OF THE TYPE A AND B ORBITS.

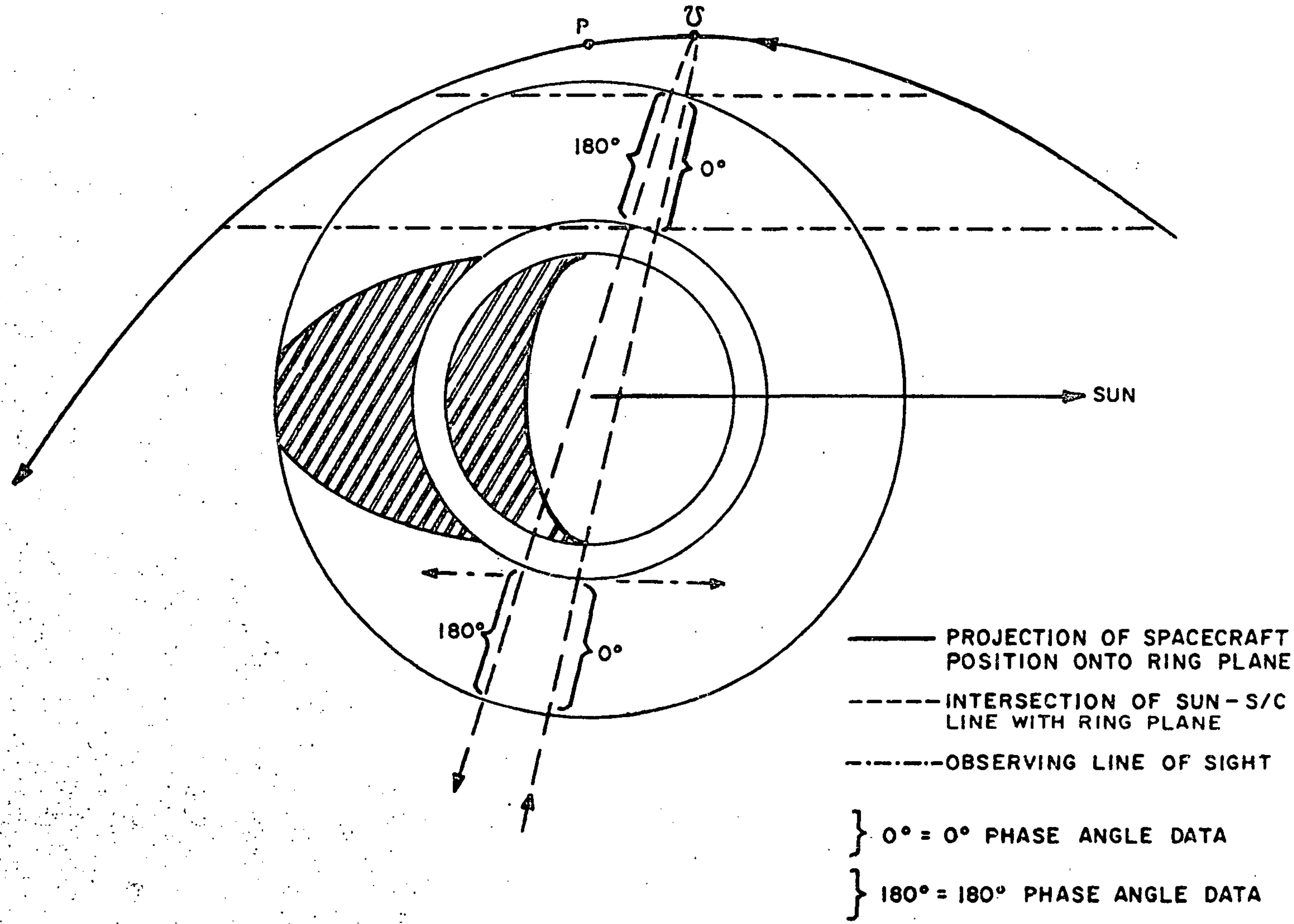

FIGURE 8. PHASE ANGLE COVERAGE FOR 1985 (A) ORBITER.

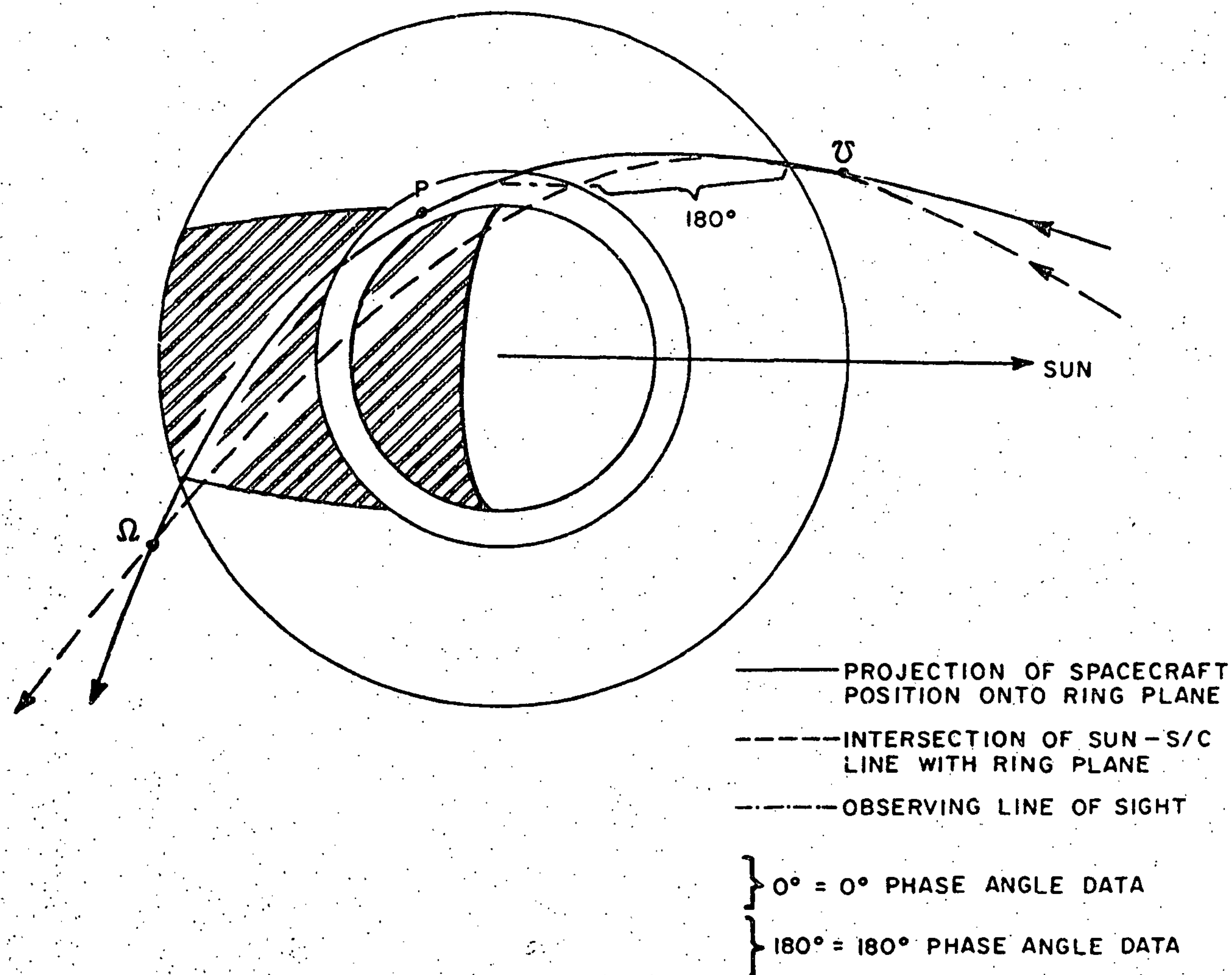

FIGURE 9. PHASE ANGLE COVERAGE FOR 1980 (B) FLYBY.

When arrival conditions do not allow extinction observations to be made with either the Type A or B trajectories, a third mode, Type C, can be employed. The spacecraft path is to a point in the ring plane just outside the rings and about 135° from the subsolar longitude. A high inclination of 30 to 45 degress is used; this is always available. The argument of periapse is approximately zero. Typical coverage for this option is depicted in Figure 10. The 1976 flyby, which has $\delta_{VHP} > \delta_{\odot}$, can obtain ring occultation data only with this Type C trajectory. There may be no planet occultation, however.

The planetocentric orbit elements required for determining the coverage were calculated from the arrival asymptote and the desired location of periapse. The arrival conditions for ballistic mission, including the location of the sun, were taken from the Planetary Flight Handbook (1969) and are presented along with the orbits in Table 3. The arrival dates are based on the analysis in Section 5. Including a probe on a 1980 flyby would change the orbital elements slightly because the flight time is longer.

4.3 Mission Operations Resulting in Ring Impacts

4.3.1 Probe Deployment

For any flyby spacecraft, the inclusion of probes can be used to obtain engineering data on the rings. The simplest deployment maneuver is one in which the trajectory plane is unchanged but the radius of the node or ring intersection is reduced. Deployment requirements were calculated for the Outer Planets missions and for a 1980 direct ballistic flyby. The results are shown in Figure 11 where in all cases deployment occurs about 20 days before Saturn encounter. The large (greater than 275 m/sec) propulsion requirement for the JSP 1977 mission is a direct result of the ten planet radii closest approach of the spacecraft. The higher impact velocities for this mission

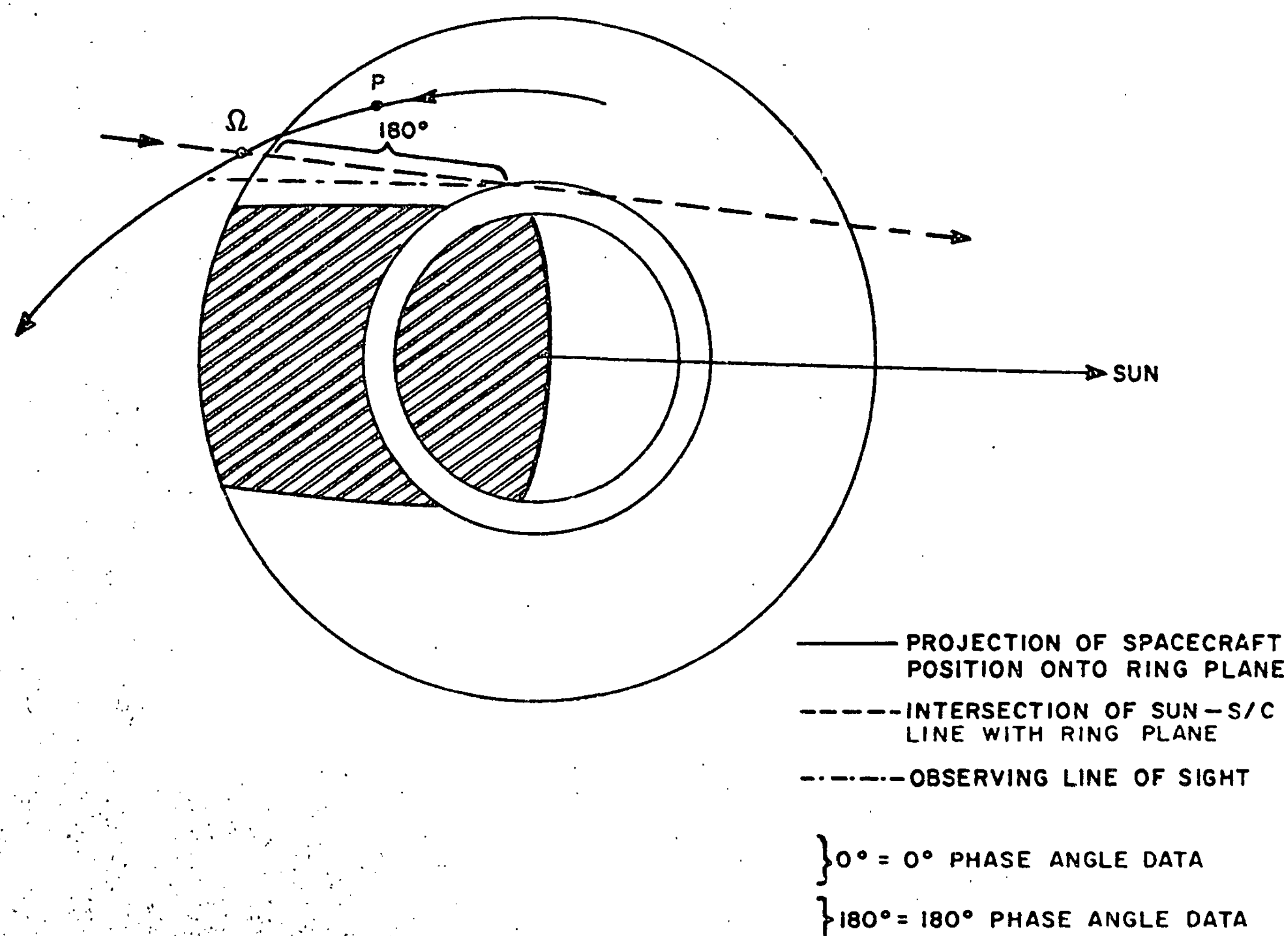

FIGURE 10. PHASE ANGLE COVERAGE FOR 1976 (C) FLYBY.

TABLE 3 ARRIVAL CONDITIONS AND ORBIT PARAMETERS FOR CANDIDATE MISSIONS

LAUNCH YEAR/ MISSION	1977 JSP	1978 JSUN	1976(C) FLYBY	1980(A) FLYBY	1980(B) FLYBY	1985(A) ORBITER	1985(B) ORBITER
ARRIVAL CONDITIONS							
Date	11/23/80	5/19/82	3/17/79	10/12/83	10/12/83	2/22/89	2/22/89
Right Ascension	-	-	146.6	194.5	194.5	236.5	236.5
Declination	-	-	13.8	-8.1	-8.1	-22.5	22.5
VHP (km/sec)	15.14	9.93	13.83	11.83	11.83	7.54	7.54
LOCATION OF THE SUN							
Right Ascension	7.4	23.6	348.3	39.2	39.2	103.5	103.5
Declination	3.7	11.3	-5.8	17.5	17.5	25.9	25.9
ORBIT PARAMETERS							
Semi-major Axis (R_s)	-2.74	-6.37	-3.28	-4.49	-4.49	31.25	30.62
Eccentricity	4.90	1.32	1.62	1.56	1.25	0.92	0.96
Inclination	56.07	29.40	45.00	17.50	10.10	25.90	25.33
Argument of Periapse	-93.72	146.50	-32.29	157.90	-90.00	206.25	-90.00
Ascending Node	204.53	3.10	132.38	347.67	247.50	357.49	298.08
Periapse Radius (R_s)	10.68	2.06	2.15	2.50	1.10	2.50	1.25

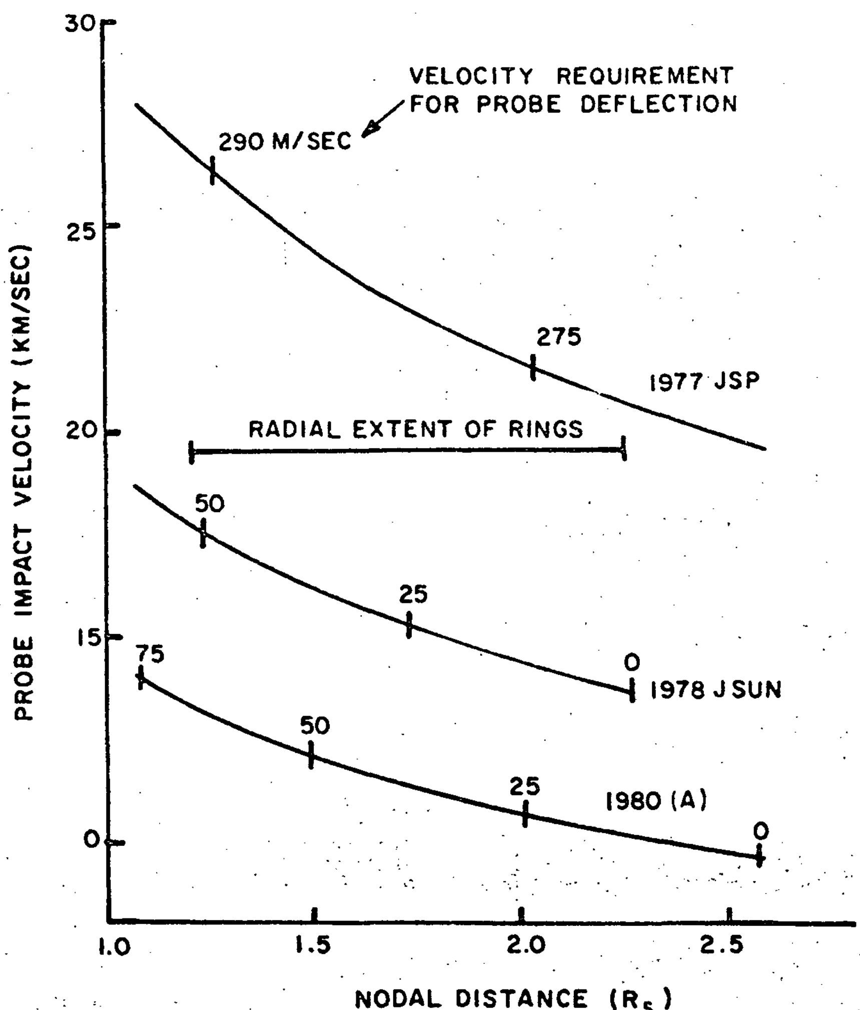

FIGURE 11. PROBE IMPACT AND DEFLECTION VELOCITIES VS. NODAL DISTANCE.

are the result of both inclination and the large radial component of probe velocity. Probe impact occurs about one day before spacecraft periapse when the probe spacecraft distance is about 25 planet radii.

The deployment velocities for either the JSUN 1978 or the 1980 (A) flyby are less than 50 m/sec. Unfortunately the node for the 1978 JSUN trajectory, and thus the impact of a ring probe, occurs where the rings are in occultation (see Figure 7). The spacecraft is still 1.0 to 1.5 hours before periapse and is not in occultation. The probe-spacecraft distance is three planet radii or less. For the 1980 (A) case the rings are illuminated while the times and distances are quite similar to the JSUN case. The Type B trajectory is not included because, for in-plane deployment, it results in atmospheric entry as well as ring impact. An out-of-plane maneuver would probably prevent this. In any event the Type B trajectory will have a large radial component of probe impact velocity. Although a Type C trajectory example has not been studied, it should be much the same as the A class, except that since a higher inclination is used, the impact velocity will be higher.

4.3.2 Orbital Maneuvers Resulting in Ring Impact

Three strategies for radial in-situ study of the rings with an orbiter have been developed. The first two, periapse lowering and perturbations on the argument of periapse, are appropriate for elliptical orbiters, but only if the particles in the ring do not represent a large hazard to the spacecraft. The third technique considered is using NEP low thrust propulsion to hover over the rings in a minor circle orbit.

A Type A orbit, initial periapse of 2.5 planet radii, is a natural choice for the periapse change method. The periapse reduction is performed at apoapse and can be done as a series of small propulsion maneuvers resulting in an ever decreasing impact radius. The total velocity requirement is the same for either a single maneuver or a series of small ones ending at the same periapse radius. The total requirement for several orbit periods is shown in Figure 12. The resulting impact velocities are also shown for zero and 30° inclination; these are not sensitive to orbit period in the range considered.

It would appear that a very low inclination would be desired to reduce the impact velocity and thus reduce damage to the spacecraft. However, the lower the inclination the longer the path through the rings; path length or mass intercepted is proportional to the cosecant of the inclination. The minimum damage can be found by minimizing the kinetic energy of the impacts, which occurs at an inclination of approximately 20°. This is very compatible with Type A orbiters launched in the 1980's.

The dynamic oblateness (J_2 = 0.027) of Saturn results in rapid perturbations in the longitude of the ascending node and the argument of periapse (ω). The latter is important as it affects the radius of nodal crossing. The Type B orbit, periapse 1.25 R_s and ω = 90°, has an initial ring intersection radius of about 2.45 R_s (this is a slight function of the orbit period). As shown in Figure 13, the second orbit after capture results in an intersection of the A ring although the actual radius depends on the inclination. For a nominal 30^d orbit period and 30° inclination or less one year in orbit results in ten ring crossings in the radius range from 2.27 down to less than 1.50 R_s or all of the A and B rings. A difference in ring impact velocity is apparent, but again to minimize damage the path length must be considered. It is interesting to note that an orbit can be adjusted at apoapse by a small change in inclination to hold the argument of periapse constant, effectively cancelling the perturbations. Less than a 1.0 m/sec velocity change per orbit is required for the Type B orbit, so that by small, but crucial

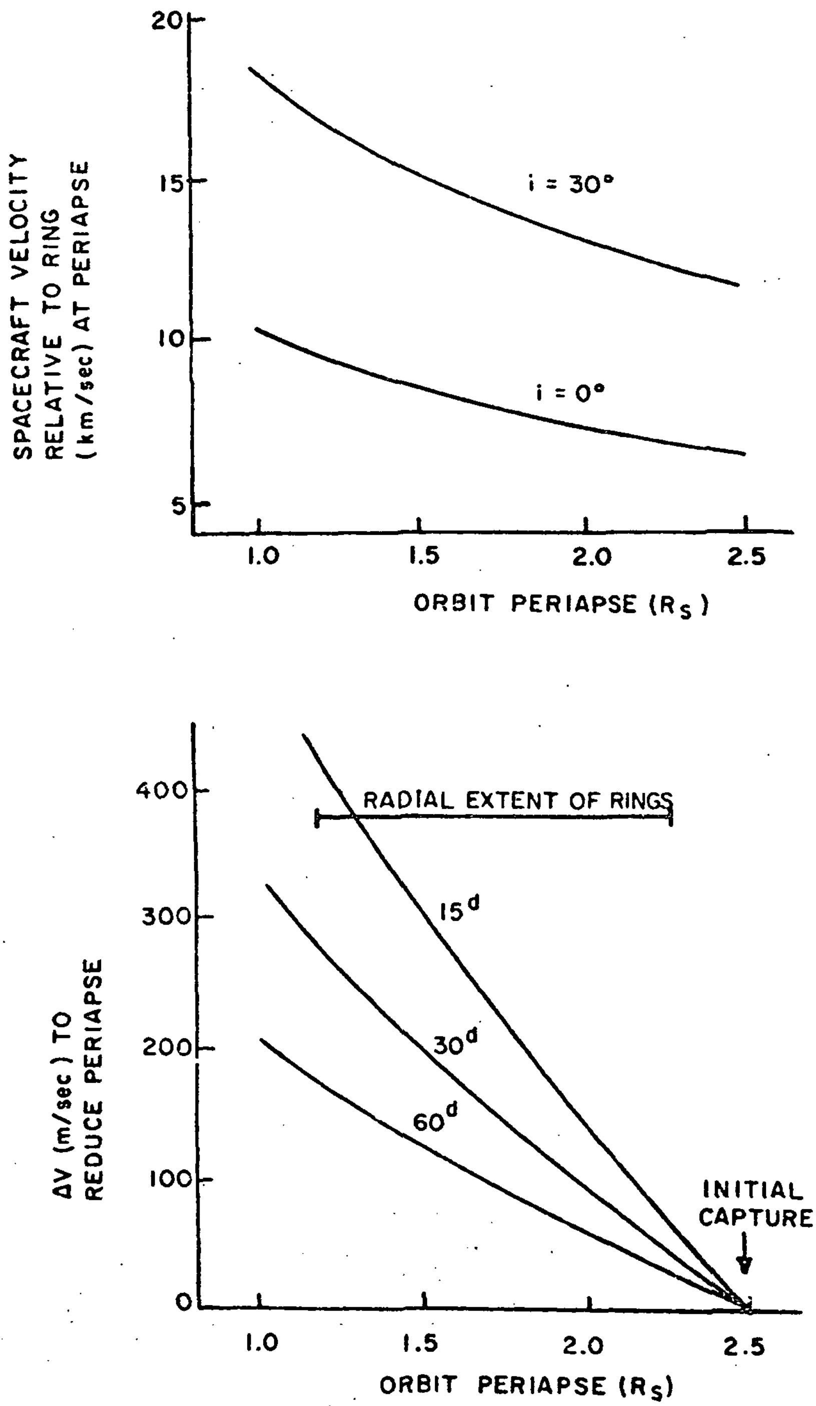

FIGURE 12. VELOCITY REQUIRED FOR PERIAPSE REDUCTION AND RESULTING RING IMPACT VELOCITY

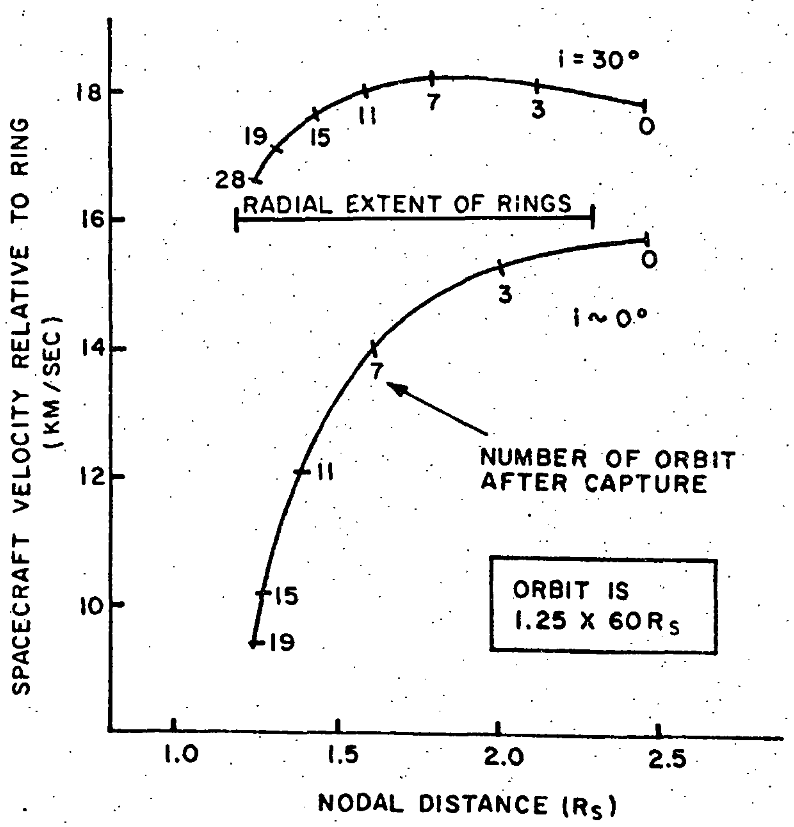

FIGURE 13. IMPACTS RESULTING FROM ORBIT PERTURBATIONS.

corrections, this orbit can be used in a mode that never intersects the rings.

Finally, for the nominal NEP circular orbiter mission it can be demonstrated that a safe minor circle orbit can be used to study the rings at very close range. The low thrust propulsion system has an acceleration of 10^{-3} m/sec^2. At a distance d above the rings and a distance R from the center of Saturn there is a vertical component of gravity (i.e., toward the rings) given approximately by

$$g_v = 10.5\ (d/R)\ (R_s/R)^2\ \text{m/sec}^2\ .$$

The constant (10.5 m/sec^2) is Saturn's surface gravity and R_s the planet radius. There is also an acceleration produced by the rings of about 4×10^{-5} m/sec^2. This is independent of d and R and was calculated for a ring system of 1.0 km thickness and 1.0 g/cm^3 average density. The ring contribution is small enough to be ignored.

The maximum value of d is found with the low thrust acceleration of 10^{-3} m/sec^2 equal to g_v . At 1.20 R_s, a distance of 9.8 km or less can be maintained between the spacecraft and the ring plane. The maximum distance increases as R^3, so at 2.27 R_s the spacecraft can be up to 66.6 km from the rings. To execute the spiral orbit capture only a fraction of the thrust can be used to maintain the minor circle orbit. But extra propellant (and time) is required when a portion of the thrust is directed toward the rings. Thus an amount equal to 50% of propellant required for Saturn orbit capture has been included in the NEP mission payload. At any time when it is desired to pass through the rings, the NEP can be turned off and the spacecraft will be in a circular, near equatorial ($i \sim 0.01°$ orbit). The relative velocity between the spacecraft and a ring particle will be approximately 3 m/sec.

4.4 Instrument Selection

The candidate instruments described in Sections 3 are combined into packages for each of the five mission concepts. The results are summarized in Table 4.

A constrained flyby with a TOPS spacecraft will most likely carry instruments primarily for planetology and interplanetary objectives. Nevertheless, most remote sensing instruments, especially a visual photometer and an IR radiometer but also a TV and an IR spectrometer, will contribute useful data on the ring system. At least for the 1977 JSP and 1978 JSUN missions no radio occultation will occur, so this latent capability will not be useful.

For the unconstrained flyby the high priority remote sensing techniques must be included, namely: photometry, radiometry and occultation. Including pressure cells will help determine if there is residual ring material beyond 2.27 R_s . These instruments can be accommodated on any spacecraft which is important because in many years only a Pioneer spacecraft can be launched with a Titan vehicle. Thus a three-axis stabilized TOPS spacecraft is not required, but if available it could also carry a TV and IR spectrometer which are lower priority instruments. The unconstrained flyby is also the best way to deliver a ring probe. The probe should be instrumented to take advantage of both impacts and occultations. Thus pressure cells, a probe-spacecraft radio link, and a solar extinction measurement should be included. Probes require no reduction in spacecraft payload.

The desired set of remote sensing instruments for an elliptical orbiter is the same as for an unconstrained flyby. If multiple passes are made through the rings with one of the two methods discussed in Section 4.3, then an impact mass spectrometer should be used so that both the mass distribution and

TABLE 4 INSTRUMENTATION OF A SATURN RING MISSION

INSTRUMENT	WEIGHT (kg.)	TECHNOLOGY LEVEL	MISSION CONCEPTS* 1	2	3	4	5
TV	22	Grand Tour	x			x	
Photometer/Polarimeter	5	Pioneer F	x	x	x	x	
IR Radiometer	3	Pioneer F	x	x	x	x	
IR Spectrometer	10	Mariner 9	x				
Radio Occultation	-	Grand Tour		x	x		
Radar/Laser	>20	New				x	x
Pressure Cells	2	Pioneer F		x			x
Impact Mass Spectrometer	5	New			x		
Sample Analysis	>25	New				x	
TOTAL WEIGHTS (kg.)			37	10	13	>75	2

* 1. Grand Tours
2. Flybys
3. Elliptical Orbiter
4. Circular Orbiter
5. Probe

composition of ring particles are determined at many radial distances. Again, the Pioneer spacecraft is adequate and in fact, is almost always the only option available.

The second generation circular orbiter mission will profit from the knowledge gained on earlier missions. Both instrument design and selection will be affected by prior knowledge. Nevertheless, a visual imaging system (TV), a laser or radar system and a set of surface sample analysis instruments all appear to be worthy choices, since each works best at the close distance and low relative velocities that are characteristic of this mission concept. Additional remote sensing instruments, especially the IR radiometer and photopolarimeter, may be useful for studying physical properties of unique particles. Some sample handling equipment is also required.

4.5 Implications for Spacecraft Subsystems

In this section the capabilities of both the Pioneer and TOPS spacecraft will be compared with the mission requirements for flybys, orbiters and as probe carriers. A small ring probe will be proposed.

The current Pioneer F/G program has as its goal a Jupiter flyby to measure the fields and particles near the planet. Flight time is typically two years. For Saturn flyby missions the flight time is typically 2.5, but for orbiters it is about 4.0 years and to that one year should be added for orbit lifetime. Thus one of the major concerns has to be spacecraft reliability. An increase in the capacity of the RTG power source is required to provide adequate power if the mission is over three years duration. Some design changes may be considered to introduce more reliable components or redundancy for the orbiters. Specific requirements cannot be identified now, but more experience with both Pioneer F/G and TOPS will give insight into long lifetime operations.

The other major difference between Jupiter and Saturn is the communications distance. If no changes are made to Pioneer F/G the maximum data rate will be 256 bits per second which may be adequate for ring exploration but would make it difficult to do other things. Adding an X-band transmitter is desired as it would improve the rate tenfold. This change should also include the addition of dual band occultation capability. For the orbiters a retro system is required to provide the 1.69 or 1.21 km/sec ΔV needed for orbit insertion for the Type A and B missions respectively. Larger RTG's, an X-band communications system and a bipropellant retro propulsion system with 2.0 km/sec capability have been considered for Jupiter orbiters (Ames, 1971). These improvements to Pioneer make the gross weight of a flyby or the useful weight (excludes inerts) of an orbiter 273 kg (600 lbs.). Note that this Pioneer spacecraft can accommodate about 55 kg of science instruments so that only a fraction of the payload is being used for ring exploration (see Table 4).

If the Pioneer spacecraft is to deploy a probe, then either significant changes must be made to the spacecraft or to normal operating procedures. As an example,probe-spacecraft communications can be handled either by adding small antennas or by orienting the main antenna to the entry point. Orientation of the spacecraft may not be accurate enough which would require changes in the attitude control subsystem. The probe deployment maneuver can likewise either be done by the spacecraft or the probe. Such choices can only be made as a result of a more detailed study. For selection of a nominal flight time in Section 5, a payload of 364 kg (800 lbs.) was assumed for Pioneer probe missions. The difference is consistent with the TOPS modification plus probe(s).

The TOPS spacecraft is being designed for the Grand Tour missions which last up to ten years and go to all the outer planets. A Jupiter orbiter has also been studied (JPL, 1971a).

No changes are required to the subsystems for the shorter Saturn ring missions. The science payload of the TOPS (60 kg) is much larger than the requirements for either the unconstrained flyby or the elliptical orbiter. In addition, the 637 kg (1400 lb) net mass is in most years beyond the capability of the Titan launch vehicle (see Section 5). An additional 90 kg (200 lbs) will be assumed for inclusion of a probe. Several atmospheric entry probe studies (e.g., Martin, 1971) have indicated that the TOPS modifications would amount to about 45 kg (100 lbs), but a reduction to 30 kg can probably be projected for a lighter ring probe.

Hard lander probes have been considered for the Moon and for Mars while atmospheric entry probes have been studied for Venus and the outer planets. Probe weight estimates have ranged from about 75 to over 400 lbs. The latter number includes an aeroshell, a pressure vessel and other subsystems which are not needed for ring probes. It seems likely that the Martin (1971) probe might shrink to about 50 kgs (110 lbs) if adjustments were made for mission requirements. About 2 kg is allotted for science instruments and a one watt transmitter is adequate. Such a probe would be compatible with a TOPS spacecraft designed for atmospheric entry probe deployment. If only one probe were used about 90 kg of additional payload is added to the spacecraft. This estimate may not apply to the 1977 JSP mission since the larger communications distance (probe to spacecraft) may not allow a reduction in transmitter power and the large deflection ΔV might also impact probe weight.

An entirely new probe concept can also be proposed, namely one which removes many burdens from the probe. Significant savings could be made by targeting the spacecraft for ring impact, deploying the probe and then retargeting the spacecraft to avoid the rings. The ΔV requirement is thus placed on the spacecraft rather than the probe. Spin-stabilization is now practical and saves weight since no attitude control system is needed on the probe. The total probe weight might be in the 5 to 10 kg range so that multiple probes could be deployed. The spacecraft modifications would be larger since more of the burden would be shifted to it. Within the 90 kg allotted for probe systems, roughly 40 kg could be the probes.

Clearly the details of the probe situation are not well defined. Some additional consideration must be given to the need for the probes; namely can an adequate engineering model be generated without a probe mission? What kind of probe is required and how much do it and the spacecraft modifications weigh? The first question should be explored by scientists planning the Grand Tour missions even though the probe concept may be far more effective on an unconstrained flyby. The second question should be put to hardware specialists.

At this time it is not possible to be very specific about the circular orbiter spacecraft or its subsystems since not enough is known about the rings to define its mode of operation. An estimate of one thousand kilograms will be used for the net spacecraft mass.

5. TRANSFER/PROPULSION SELECTION

In this section ballistic flybys of Saturn are discussed, then ballistic orbiters and finally a nuclear electric (NEP) orbiter. Launches in 1976, 1980 and 1985 were considered for the ballistic missions. The first two opportunities come before and after the Grand Tour launches. For a launch between 1976 and 1980 the solar illumination of the rings will be poor when the spacecraft arrives. 1985 is the most favorable launch opportunity in its decade. The Titan IIID in either the five or seven segment version is used as the launch vehicle while the upper stages for the ballistic missions are the Centaur/ Burner II. All of the results for the ballistic missions are calculated from the Type I trajectory data in the Planetary Flight Handbook (1969) which tabulates launch and arrival conditions for selected arrival dates. The declination of the earth departure asymptote (DLA) was not allowed to exceed 40° so in some cases the twenty day launch window did not open and close at the same energy. In the 1980's the Space Shuttle may replace the Titan vehicles with no penalty and probably some improvement in payload for these missions.

5.1 Saturn Flyby Missions

Flyby payloads are shown in Figure 14 for both 1976 and 1980 launches with Titan class launch vehicles. A Pioneer spacecraft can be delivered by a Titan IIID/Centaur/Burner II in either year, but probes can be carried only in 1980. The seven segment version could be used to cut the flight time or to deploy probes in 1976 although this was not considered in this study. Delivery of the TOPS spacecraft is beyond the Titan IIID(7)/Centaur/Burner II capability until the mid 1980's (sufficient payload was found in 1985 at 1250 days). The alternative is solar electric propulsion which requires about a 1200 day flight to deliver the TOPS spacecraft using a 15 kw stage and the Titan IIID/Centaur (TRW, 1971).

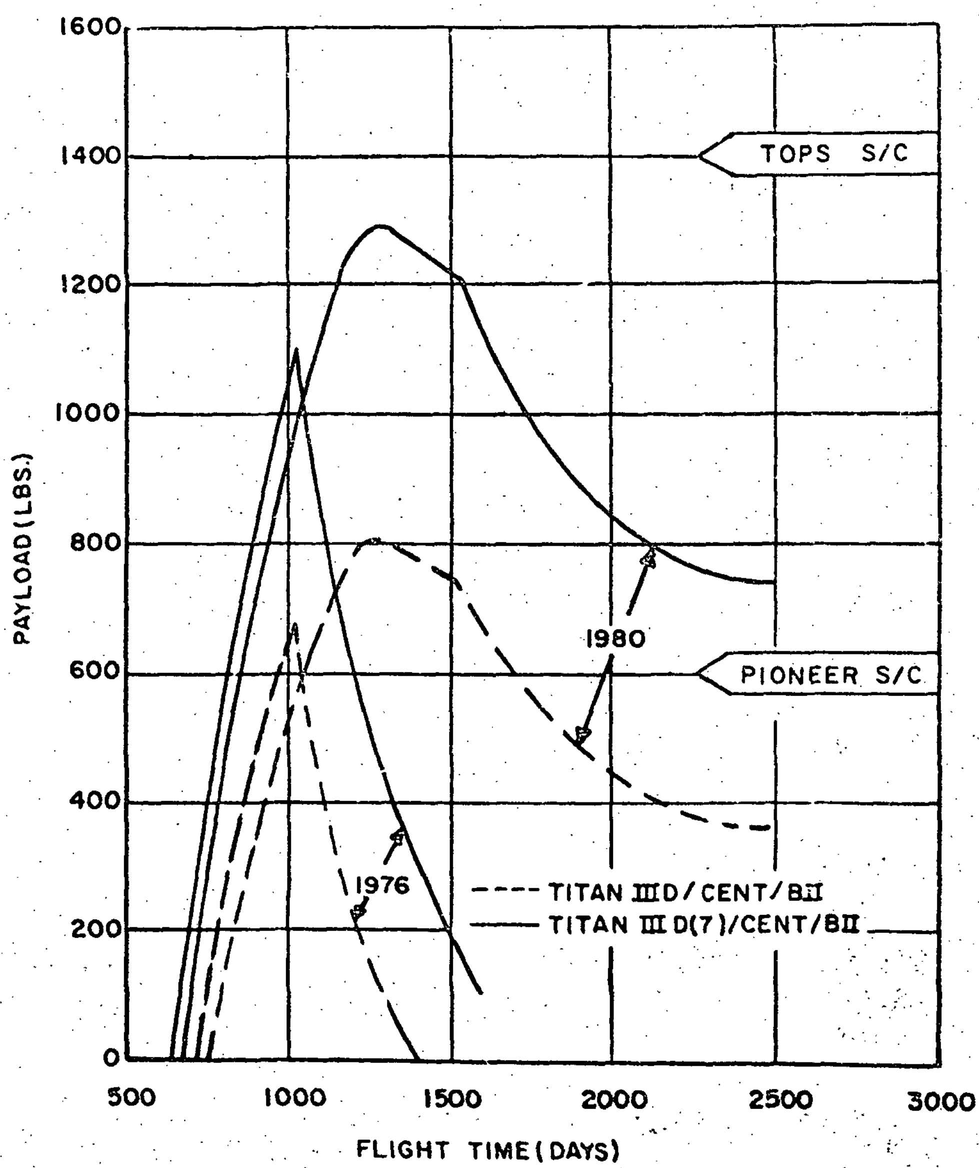

FIGURE 14. PAYLOAD SUMMARY FOR SATURN RING FLYBY MISSION.

In 1976 the decrease in payload for flight times greater than one thousand days is caused by the DLA constraint. However removing the constraint can at most result in a 12% increase in payload (to 1240 lbs). Thus the primary effect is a limited choice of flight times and arrival velocities. The DLA constraint appears after 1500 days of flight time in the 1980 opportunity.

For the nominal missions which are summarized in Table 5 preference is given to the smaller Titan vehicle and the shortest flight time which gives sufficient payload. But since all the baseline flybys are Pioneers, the TE364-4 could be employed instead of the Burner II upper stage which would give some improvement in launch vehicle performance (about 200 lbs of injected payload). This change would in effect allow probes to be added to the 1976 flyby and reduce the flight time for the 1980 probe mission by 200 days.

5.2 Elliptical Orbiter Missions

Two orbits were defined in Section 4.2. Orbit A has a 2.50 R_s periapse, B has a 1.25 R_s periapse and both have a 30 day period. In Figure 15 the net spacecraft weight in orbit, which does not include any propulsion system weight, is given for 1980 and 1985 launches. All launches are made with the Titan IIID(7)/Centaur/Burner II and orbit captures made with an earth-storable bipropellant retro propulsion system (I_{sp} = 285 sec). The total ΔV capability of the Type A orbiter is about 2.0 km/sec which includes 0.3 km/sec for midcourse corrections and orbit periapse reduction to about 1.50 R_s. The Type B orbiter's ΔV is only 1.3 km/sec and includes 0.1 km/sec for midcourse maneuvers.

With the assumptions used in Figure 15, it is possible to place a Pioneer spacecraft into Orbit A in 1985 only and into Orbit B in both years. In fact 1985 (B) can be done with

TABLE 5 SUMMARY OF CANDIDATE MISSION REQUIREMENTS

CANDIDATE MISSIONS	FLIGHT TIME	LAUNCH VEHICLE	CAPTURE I_{sp}	VHP	NET PAYLOAD
1976 Flyby	980^d	5+	-	13.8 kps	620 lbs.
1980 Flyby	1040	5	-	13.6	600
with Probe	1240	5	-	11.8	810
1980 Orbiter (A)*	1490	7	385	8.7	590
(B)	1490	7	285	8.7	600
1985 Orbiter (A)	1500	7	285	8.3	630
(B)	1500	5	285	8.3	640
NEP Orbiter#	2100	#	#	0.0	2640

* Orbit A has 2.50 R_s Periapse, 30d Period
Orbit B has 1.25 R_s Periapse, 30d Period

\+ 5 = Titan IIID/Centaur/BII
7 = Titan IIID(7)/Centaur/BII

\# Shuttle/Centaur, P = 100 kw, I_{sp} = 4500 sec., R_p = 1.25 R_s .

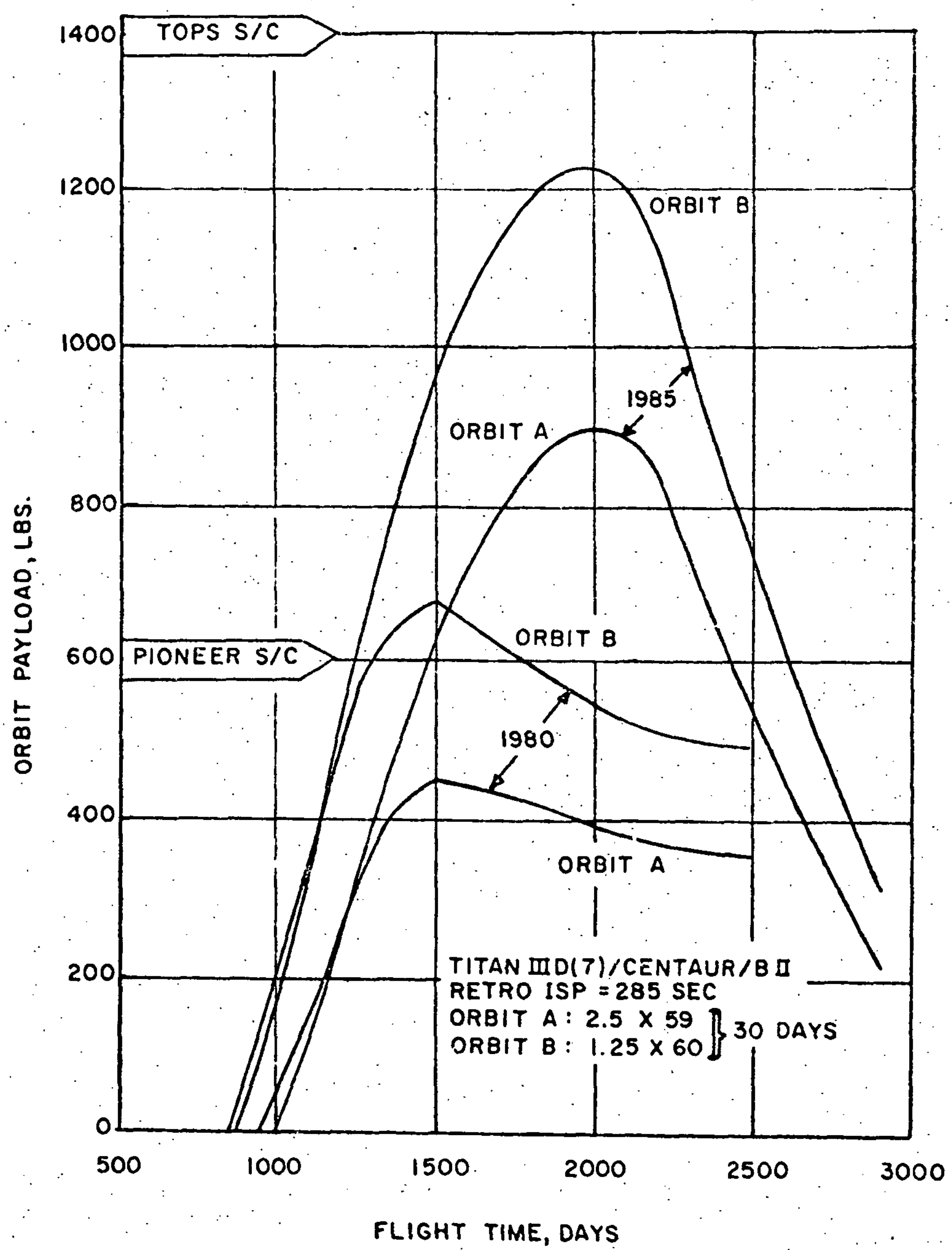

FIGURE 15. PAYLOAD SUMMARY FOR SATURN RINGS ORBITER MISSIONS.

the five segment version and this is reflected in our nominal mission selections. If space-storable propellants (I_{sp} = 385 sec.) are available in 1980, Orbit A can be achieved. The DLA constraint in 1980 results in less than a 10% reduction in the maximum payload in orbit.

The choice of orbit period (30 days nominal) represents a trade-off of payload against frequency of periapse passes. Increasing the period to 120 days results in a marginal 10% payload increase while a reduction by a factor of four (to 7.5 days) causes about a 30% reduction in payload. The retro propulsion system trade-off shows that space-storable is best, then solids (including auxiliary vernier thrusters) and last earth-storable. But from a technology standpoint earth-storable is preferred for the Pioneer spacecraft.

A TOPS spacecraft with a space-storable retro propulsion system can be placed in Orbit B in 1985 but is otherwise too heavy for the Titan class vehicles. Again SEP is needed but to deliver a net 637 kg with the 15 kw stage will require from 1600 to 2000 days depending on whether the stage has zero to 400 kg net mass of its own (JPL, 1971b; TRW, 1971) and on the type of orbit chosen for the mission.

5.3 Circular Orbiter Missions

Nuclear electric propulsion (NEP) is the obvious choice to deliver a large exploration package to a circular equatorial orbit at 2.50 R_s and then spiral inward to 1.25 R_s, using a minor circle orbit if necessary. Calculations were made for two power levels (100 and 250 kw) and for flight times of 1600 to 3600 days. The results given in Figure 16 are launch year independent since the reasonable assumption of circular, coplanar orbits for the Earth and Saturn was used.

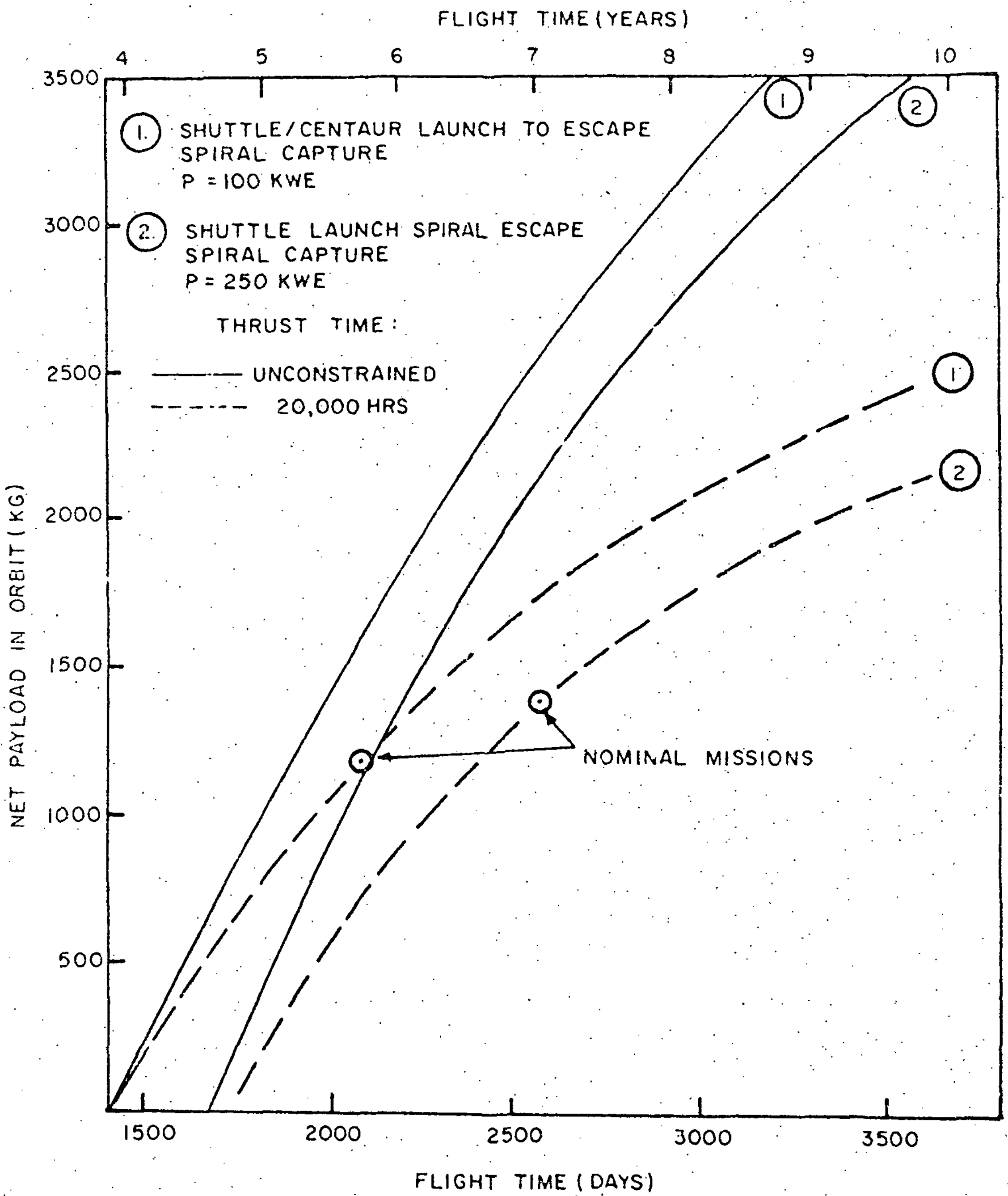

FIGURE 16. SATURN RING TRANSIT: NEP PAYLOAD CAPABILITY.

For the lower power level (100 kw) the Shuttle/Centaur combination is employed for Earth escape (VHL = 3.0 km/sec). To put a Centaur and NEP system, including a payload of 1200 kg, into a parking orbit requires a maximum performance shuttle without air breathing engines. The flight time is about 2100 days if the thrust time is constrained at 20,000 hrs. and the thruster specific impulse (I_{sp}) is 4500 sec. For the higher power level, the 13,600 kg NEP system (including the payload) is delivered to a 500 km parking orbit by a nominal shuttle after which spiral escape is performed. Flight time is 2600 days for the constrained thrust time at an I_{sp} of 7000 sec. Shorter flight times and higher I_{sp}'s result if the thrust time constraint is removed.

Calculations were also made using the Titan IIID(7) launch vehicle. Its performance is better than the nominal shuttle for the higher power level but far worse than the maximum performance Shuttle/Centaur for the 100 kw mission. The flight times required when the thrust time was constrained to 20,000 hrs. were about 2200 and 3300 days respectively.

6. CONCLUSIONS AND RECOMMENDATIONS

Saturn's ring system is an interesting phenomenon with implications for the origin and evolution of the solar system. To understand the current state of ring system requires quantitative earth-based observations and especially space missions to Saturn. With better knowledge of the physical properties of individual particles (i.e., size distribution, mass distribution, composition, shape and structure), the spread in orbital parameters and the spatial distribution of particles, it should also be possible to infer the origin and evolution of the ring system. For first generation missions the most important measurement techniques are photopolarimetry, radiometry, radio occultation and meteoroid impact detection. Visual imagery and spectroscopy are useful.

There are two very desirable flyby trajectories or orbits. The better one stays near the ecliptic plane and generates complete phase angle coverage of the rings as required for the remote sensing techniques. Data are obtained for zero degrees (backscatter), 180° (extinction) and all intermediate phase angles over the full radial extent of the rings. The in-situ (impact) measurements can be accomplished by deploying a probe twenty days before encounter which requires a ΔV of 50 m/sec or less or by reducing the periapse of an orbiter with a 30 day period from the nominal 2.5 R_s to 1.5 R_s which requires about 200 m/sec. The second candidate has a low periapse and a 90° argument of periapse. The phase angle coverage is not complete, but the rings are observed at closer distances and the orbit capture is easier. Orbit perturbations, if not controlled, will result in useful ring impacts.

Both the 1977 JSP and the 1978 JSUN Grand Tour missions have less than full phase angle coverage and in particular have no occultations of the sun and earth by the rings. The JSUN mission does allow a better examination of the rings at much closer distances and is much better for probe deployment for the same reason.

For direct flybys and orbiters of Saturn to study the rings, a Pioneer spacecraft appears sufficient. It can easily accommodate the high priority instruments which are a photo-polarimeter, an IR radiometer, a dual band radio transmitter, and a meteoroid impact detector. Improvements in the Pioneer radio transmitter are desirable to increase the data rate and for orbiters the lifetime of the RTG's and perhaps of other components must be extended. A more detailed study of deployed ring probes is required to determine the probe characteristics and the associated spacecraft modifications.

The first step in the exploration of the ring system should be a flyby with a deployed probe. The 1980 opportunity should have typical requirements for this mission. They are a Titan IIID/Centaur/Burner II launch vehicle and about a 1240 day flight time. An elliptical orbiter could follow and although using many of the same techniques would return more detailed data on the rings. An earth-storable retro propulsion system is needed for orbit capture after approximately a 1500 day interplanetary transfer. In 1980 the Titan IIID(7)/Centaur/Burner II is the launch vehicle required and only the low periapse orbit is available. But in 1985 either orbit is possible, the low periapse orbit can be achieved with the five segment Titan. With rare exceptions, the TOPS spacecraft is beyond the capability of the Titan launch vehicles, although the addition of solar electric propulsion allows TOPS to be used for flybys and elliptical orbiters.

After approximately 1990 consideration should be given to the second generation ring exploration mission concept which is the circular equatorial orbiter. The remote sensing instruments can now measure individual ring particles and the in-situ measurements can be quite sophisticated. This mission requires nuclear electric propulsion (100 to 250 kw) not only for the trip to Saturn, but also for the spiral orbit capture and concurrent radial study of the rings. The Space Shuttle can be used for the launch.

While this study has concentrated on ring system exploration, many of the proposed missions do not use the full capability of the spacecraft to gather scientific data. Future studies of space missions to Saturn should use the principles established for useful ring system exploration and develop mission concepts which also study Saturn, its magnetosphere and its satellites.

REFERENCES

Allen, C. W. (1963), Astrophysical Quantities, 2nd Edition, (Athlone Press, London).

Ames, (1971), presentation to the Science Advisory Group, 29 July 1971.

Banderman, L. W. and Wolstencroft, R. D. (1969), Bull. Am. Astron. Soc. 1, 233. (Abstract).

Camichel, H. (1958), Ann. d'Astrophys. 21, 231.

Campbell, W. W. (1896), Astrophys. J. 2, 127.

Cook, A. F. and Franklin, F. A. (1958), Smithsonian Contr. to Astrophys. 2, No. 13.

Cook, A. F. and Franklin, F. A. (1964), Astron. J. 69, 173.

Cook, A. F. and Franklin, F. A. (1966), Astron. J. 71, 10.

Cook, A. F. and Franklin, F. A. (1970), Astron. J. 75, 195.

Dollfus, A. (1961a), "Polarization Studies of Planets," in Planets and Satellites, Ed. G. P. Knipes and B. M. Middlehurst, (Univ. of Chicago Press: Chicago), 343-399.

Dollfus, A. (1961b), "Visual and Photographic Studies of Planets," in Planets and Satellites, Ed. G. P. Knipes and B. M. Middlehurst, (Univ. of Chicago Press: Chicago), 534-571.

Focas, J. H. and Dollfus, A. (1969), Astron. and Astrophys. 2, 251.

Franklin, F. A. and Colombo, G. (1970), Icarus 12, 338.

Franklin, F. A., Colombo, G., and Cook, A. F. (1971), Icarus 15, 80.

Franklin, F. A. and Cook, A. F. (1965), Astron. J. 70, 704.

Guerin, P. (1970), Sky and Telescope 40, 88.

Hall, J. S. (1970), Private Communication.

Hall, J. S. and Riley, L. A. (1969), J. Atm. Sciences 26, 920.

Harrison, H. and Schoen, R. I. (1967), Science 157, 1175.

JPL (1971a), Presentation to the Science Advisory Group, 29 July 1971.

JPL (1971b) Solar Electric Multimission Spacecraft (SEMMS), JPL Report No. 617-2, 30 July 1971.

Keeler, J. A. (1895), Astrophys. J. 1, 416.

Kiladze, R. I. (1967), Astron. Circ. (Russian) No. 439.

Kuiper, G. P. (1952) in The Atmospheres of the Earth and Planets, 2nd Edition, Ed. G. P. Kuiper (Univ. of Chicago Press: Chicago), p. 306.

Kuiper, G. P., Cruikshank, D. P., and Fink, U. (1970a), Sky and Telescope 39, 14.

Kuiper, G. P., Cruikshank, D. P., and Fink, U. (1970b), Sky and Telescope 39, 80.

Lebofsky, L. A., Johnson, T. V., and McCord, T. B. (1970), Icarus 13, 226.

Lumme, K. (1970), Astrophys. and Space Science 8, 90.

Lyot, B. (1929), Ann. Obs. Meudon 8.

Maxwell, J. C. (1859), On the Stability of the Motions of Saturn's Rings (MacMillan and Company, Cambridge and London).

Mie, G. (1908), Ann. Physik 25, 377.

Owen, T. (1965), Science 149, 974.

Pilcher, C. B., Chapman, C. R., Lebofsky, L. A. and Kieffer, H. H. (1970), Science 167, 1372.

Planetary Flight Handbook (1969), NASA SP-35, Part 7, Direct Trajectories to Jupiter, Saturn, Uranus, and Neptune.

Price, M. J. (1971), The Physical Structure and Implied Navigational Hazard of the Saturn Ring System, AS/IITRI Report No. P-36

Seeliger, H. von (1887), Abhandl Bayer, Akad. Wiss., Kl II, 16, 405.

Seeliger, H. von (1893), Abhandl Bayer, Akad, Wiss., Kl. II, 18, 1.

TRW (1971), Study of a Common Solar-Electric-Propulsion Upper Stage for High-Energy Unmanned Missions, Vol. II, Final Report on Contract NASZ-6040, 14 July 1971.

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