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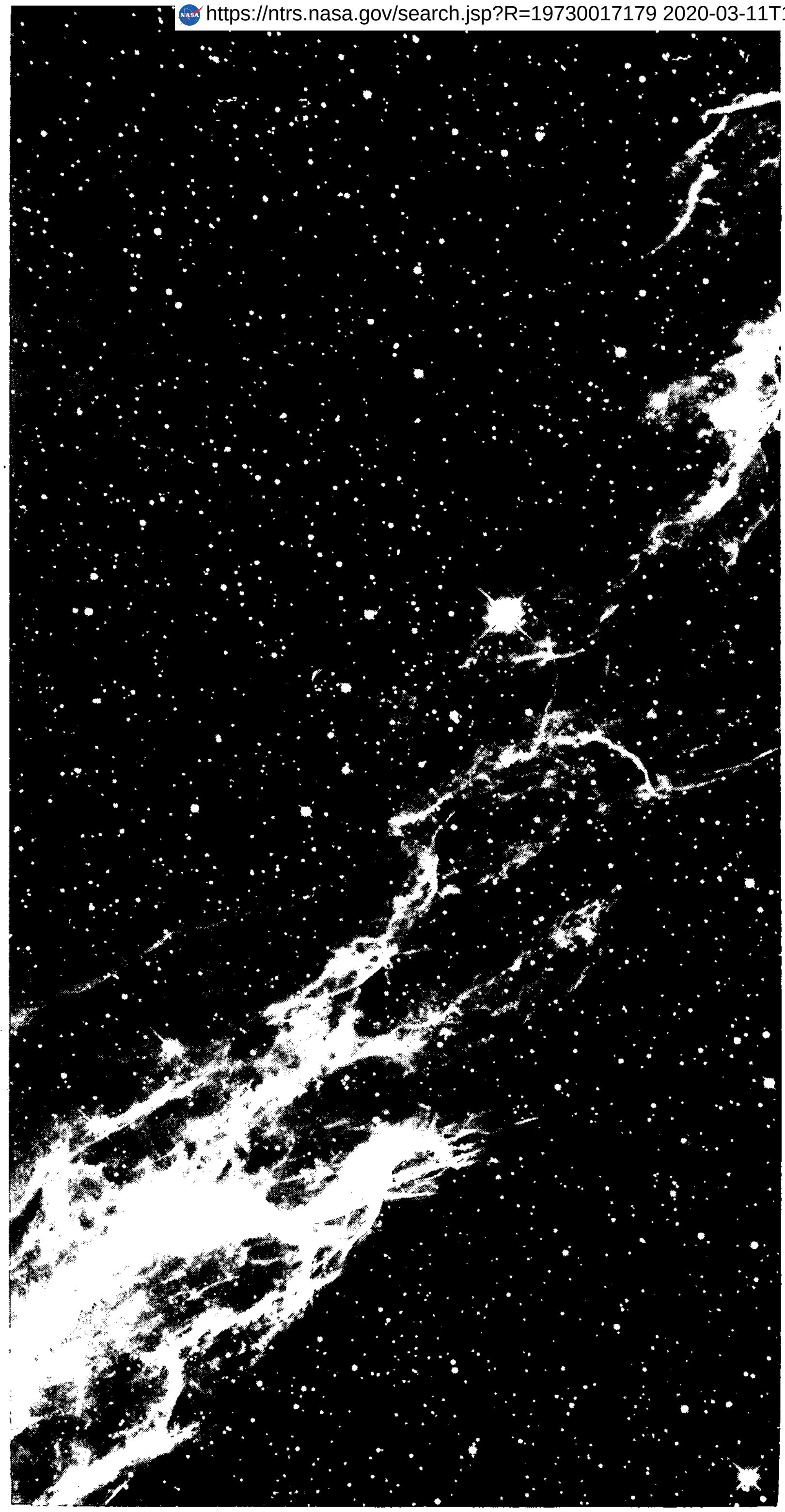

Technical Memorandum No. M-36

SATURN ORBITER MISSION STUDY

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SATURN ORBITER MISSION STUDY

by

William C. Wells
Roger J. Sullivan

Astro Sciences
IIT RESEARCH INSTITUTE
Chicago, Illinois 60616

for

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

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APPROVED BY:

C. A. Stone

C. A. Stone, Director
Physics Research Division

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FOREWORD

This technical memorandum covers work performed from October 1971 to October 1972 on one task of NASA contract number NASW-2144, Long Range Planning for Solar System Exploration. It is intended that this report complement previous studies of Jupiter orbiter missions and be useful in planning a comprehensive program for exploration of the outer planets in the 1980's.

SUMMARY

This report provides a preliminary analysis of the important aspects of missions orbiting the planet Saturn. Orbital missions to the outer planets can be given serious consideration in the 1980's or after flybys by Pioneer 10/G and Mariner Jupiter-Saturn '77. Previous studies (by IITRI/Astro Sciences, JPL and NASA/Ames) have looked at Jupiter orbiters. This effort attempts to characterize Saturn orbiters in similar detail so that comparisons with Jupiter missions can be made.

Broadly speaking, the scientific objectives of Saturn exploration can be grouped under four topics: 1) the atmosphere, 2) the magnetosphere, 3) the rings and 4) satellites. Like Jupiter, Saturn has an atmosphere consisting of belts and zones whose global circulation pattern and local features can be studied by long term monitoring (imagery) from an orbiting spacecraft. The vertical profiles of temperature, pressure, etc., can be deduced from spectroscopic and occultation measurements. Saturn's magnetic field and radiation belts, for which only upper limits can be given, could be very similar to Jupiter's and can be investigated using standard fields and particles measurement techniques. The rings are the truly unique feature of the Saturn system and the primary objective is to describe their photometric properties from which the sizes, shapes and composition of particles can be inferred. Saturn has ten satellites including Titan, the largest, which has an atmosphere; Iapetus, known for its large amplitude light curve, and Janus which is so small and close to the rings that it has been seen only four times. Imagery is the most useful technique for studying the satellites.

A suggested visual imaging instrument has been designed around the standard Mariner vidicon. Two identical 30 cm focal length lenses are used, similar to the arrangement for MVM '73. Saturn fills the field of view at a range of 60 R_s, a typical apoapse distance, where the surface resolution is 330 km per line pair. However, if the spacecraft is spin stabilized, a multi-detector spin scan camera should be used. Its resolution at the same distance is 700 km per line pair. The weight of each candidate instrument and an example of a similar one are given in Table S-1.

For accurate photometric measurements a separate photo-polarimeter with five or more spectral bands is needed. It and the selected infrared (IR) radiometer have a 0.5° field of view or a resolution of 3000 km at 6 R_s. The radiometer has a signal to noise ratio of at least 100 in two bands, 20-35 μm and 60-100 μm. Radio occultation and radio tracking data are derived from an analysis of the dual frequency radio signal received at the earth. A microwave radiometer channel at 13 cm can and should be added to the spacecraft command receiver.

An ultraviolet (UV) spectrometer, which has fixed detectors for measuring specific emission and absorption lines of H, H_2, He and other less abundant species, is easily constructed with 20 Å spectral resolution. A 1/3 x 3° field of view is appropriate even though an atmospheric scale height is not resolved during airglow measurements of Saturn's limb. It is very difficult to get both good spectral and spatial resolution in the IR, even with an interferometer. The best option is to measure absorbed solar radiation between about 2 and 6 μm. The magnetosphere, its interaction with the solar wind and its trapped particles are measured with a complementary set of instruments including a magnetometer, charged particle detectors and radio receivers to record plasma waves and planetary emissions.

Table S-1

INSTRUMENTS FOR SATURN ORBITERS

Instrument	Weight (kg)	Payload #1	Payload #2	Similar Instruments
TV System	30	x	-	Mariner 9
Spin Scan	12	-	x	ATS
Photopolarimeter	4	x	x	Pioneer 10
IR Radiometer	4	x	x	Pioneer 10
Radio Science	-	x	x	Viking
UV Spectrometer	4	x	a	Mariner '73
IR Spectrometer	15	x	-	Mariner 9
Magnetometer	3	x	x	Pioneer 10
Charged Particles	5	a	x	Pioneer 10
Plasma Wave	4	a	x	OGO
Radio Astronomy	3	a	x	RAE
Micrometeoroid Detector	5	a	x	Helios
Total - Mariner	60	x	-	
	77	all	-	
Total - Pioneer	36	-	x	
	40	-	all	

x = selected

a = alternate

Finally, there is a micrometeroid composition detector which determines the mass of ions formed by hypervelocity impacts.

Two payloads have been selected from these candidate instruments. The first emphasizes atmospheric measurements and is intended for a Mariner spacecraft which has inertial stabilization, a science payload capacity of 60 kg and the required 65 w of power. The fields and particles instruments are well represented in the second payload which is made up of experiments which can work well on the spin stabilized Pioneer spacecraft. The pointing requirements of the TV system and IR spectrometer prevent them from being alternate instruments for the Pioneer payload. Their weight is also a problem.

The rings of Saturn are a hazard to an orbiting spacecraft which crosses the equatorial plane at a radius of less than 2.3 R_s. Because of uncertainties about the full spatial extent of the rings a nodal radius of 3.0 R_s was selected for nominal missions and 4.0 R_s for a worst case analysis. Microwave observations of Saturn have not established the presence of radiation belts, but the upper limits are consistent with the nominal model for Jupiter's trapped particles. A spacecraft with a periapse of 3.0 R_s or more can survive for at least ten orbits in the nominal environment. Because the rings cut off the belts at 2.3 R_s, a periapse of 1.6 R_s can also be used. For a worst case analysis a periapse of four Saturn radii is appropriate.

There are three types of orbits that are useful for Saturn orbiter missions. The first maximizes the phase angle coverage for atmospheric and ring system measurements by using an orbit plane that passes very near the subsolar point. Figure S-1a shows that the spacecraft's motion, as typically seen from the sun, passes in front of the rings and Saturn's disc so that 0° phase angle data is obtained over the full radial extent of the rings.

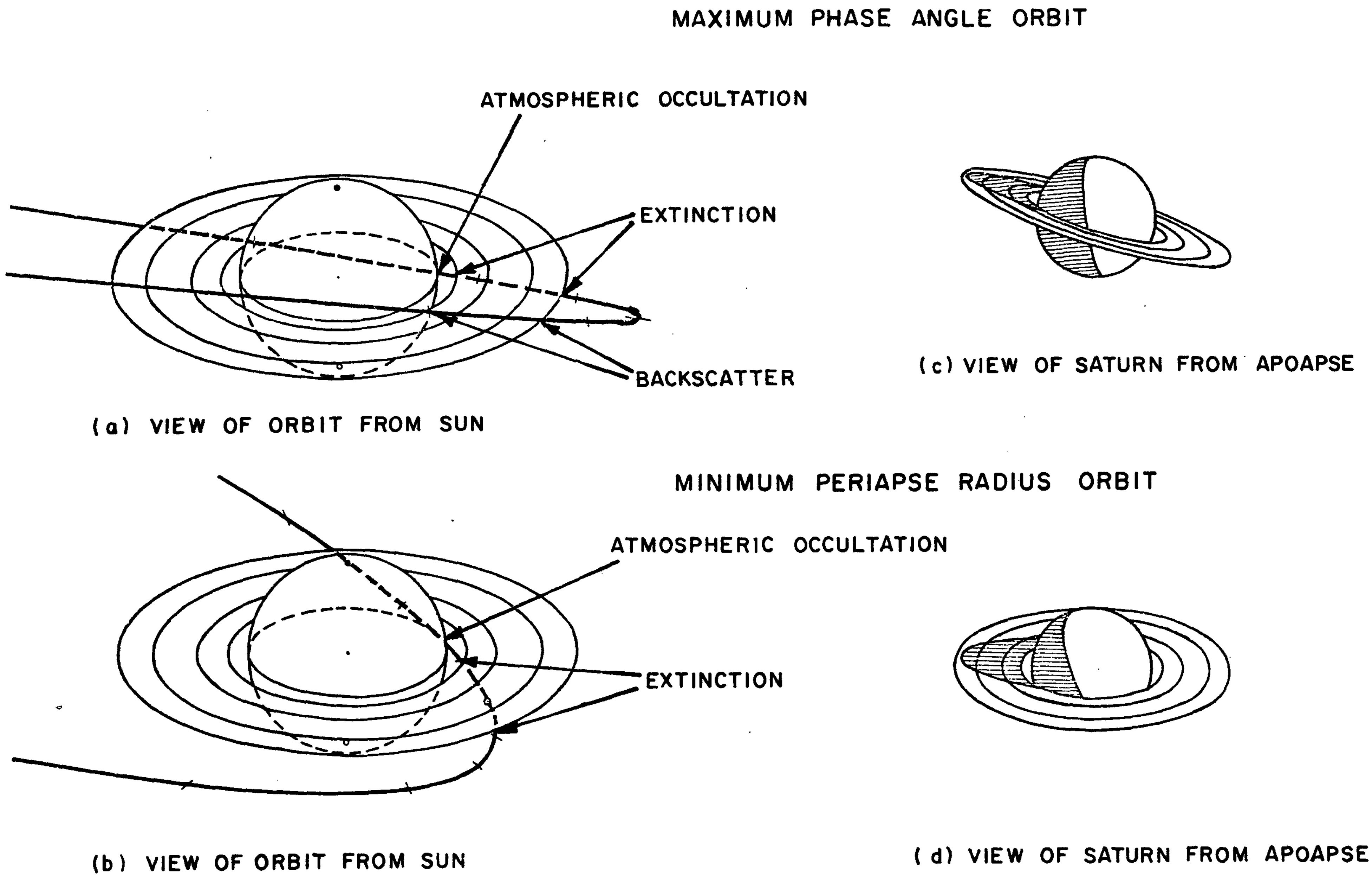

FIGURE S-1. VIEWING CONDITIONS FOR CANDIDATE ORBITS

Then the spacecraft passes behind the rings and both solar extinction and radio occultation measurements can be made. Such an orbit should have a periapse radius of 3.0 R_s and a period of 15 to 30 days. During the long periods of time near apoapse the spacecraft is well positioned to observe the global atmospheric circulation pattern (see Figure S-1b). Close passes of Titan, the largest satellite, can often be arranged in conjunction with this orbit.

Taking the periapse as 1.6 R_s minimizes the energy requirement for orbit capture. But the orbit plane is then restricted so that the node is at 3.0 R_s. Typically this type of orbit does not have complete phase angle coverage. The view from the sun in Figure S-1c shows that no 0° coverage is acquired. From apoapse the view is about the same as the previous case. A particular advantage of this orbit is the fact that it penetrates the magnetic field to the 2.15 R_s shell and can observe the effects of the rings on the trapped particles. Close encounters with the larger satellites are not possible.

Finally for maximizing the number of close encounters with satellites, an equatorial orbit is essential. This requires two additional impulses to first change the plane and then reduce the orbit period to about 16 days which is an integer multiple of the period of five satellites. The equatorial orbit also has a view of the atmosphere unobstructed by the rings but with the polar regions always foreshortened.

The first payload option could be used on each of the three candidate orbits although it might be profitable to include the fields and particles instruments on the minimum periapse radius orbit. The net mass (excluding propulsion) of a Mariner spacecraft which can provide data storage for 5×10^8 bits, data transmission at 45 kbps and $\pm$ 0.8 mrad pointing for these instruments is estimated to be 608 kg. Most subsystems would be very similar to the MJS '77 ones. The larger propulsion system would require structural changes similar to the difference between 1969 Mars flyby and the 1971 orbiter. A proposed MJS '77 revision of the radio system was assumed which would improve its scientific capabilities and decrease its weight.

The second payload option belongs on a Pioneer spacecraft in the minimum periapse or maximum phase angle coverage orbit. Significant changes to the current Pioneer 10/G spacecraft are required to convert it to a Saturn orbiter. A maximum data rate of 12 kbps is provided by a new 10 w X-band transmitter and storage is increased to 3×10^5 bits. Two MHW RTG's are employed to achieve 230 w of spacecraft power at end of mission. Structural changes caused by the larger power source and orbit capture propulsion system bring the net mass in orbit to an estimated 312 kg (excluding propulsion).

The optimum year for direct ballistic trajectories to Saturn is 1985. Launch vehicle performance for this opportunity and the spacecraft requirement are both plotted in Figure S-2, as approach mass versus approach speed. The flight time can be determined from the intersection of one curve with another. A Pioneer spacecraft can be placed into orbit after a four-year flight and a Titan III E/Centaur/TE-364 launch. The more powerful Shuttle/Centaur/HE BII reduces the flight time to 3.3 years.

The Shuttle/Centaur/HE BII is just able to put a Mariner spacecraft into this orbit. For a flight time of 4.2 years, the minimum periapse radius orbit can be achieved. Actually it will be difficult to state the Shuttle performance until its operating requirements, such as launch window and the availability of a larger chemical or nuclear state (neither of which is well defined) are determined. Solar electric propulsion, however, is capable

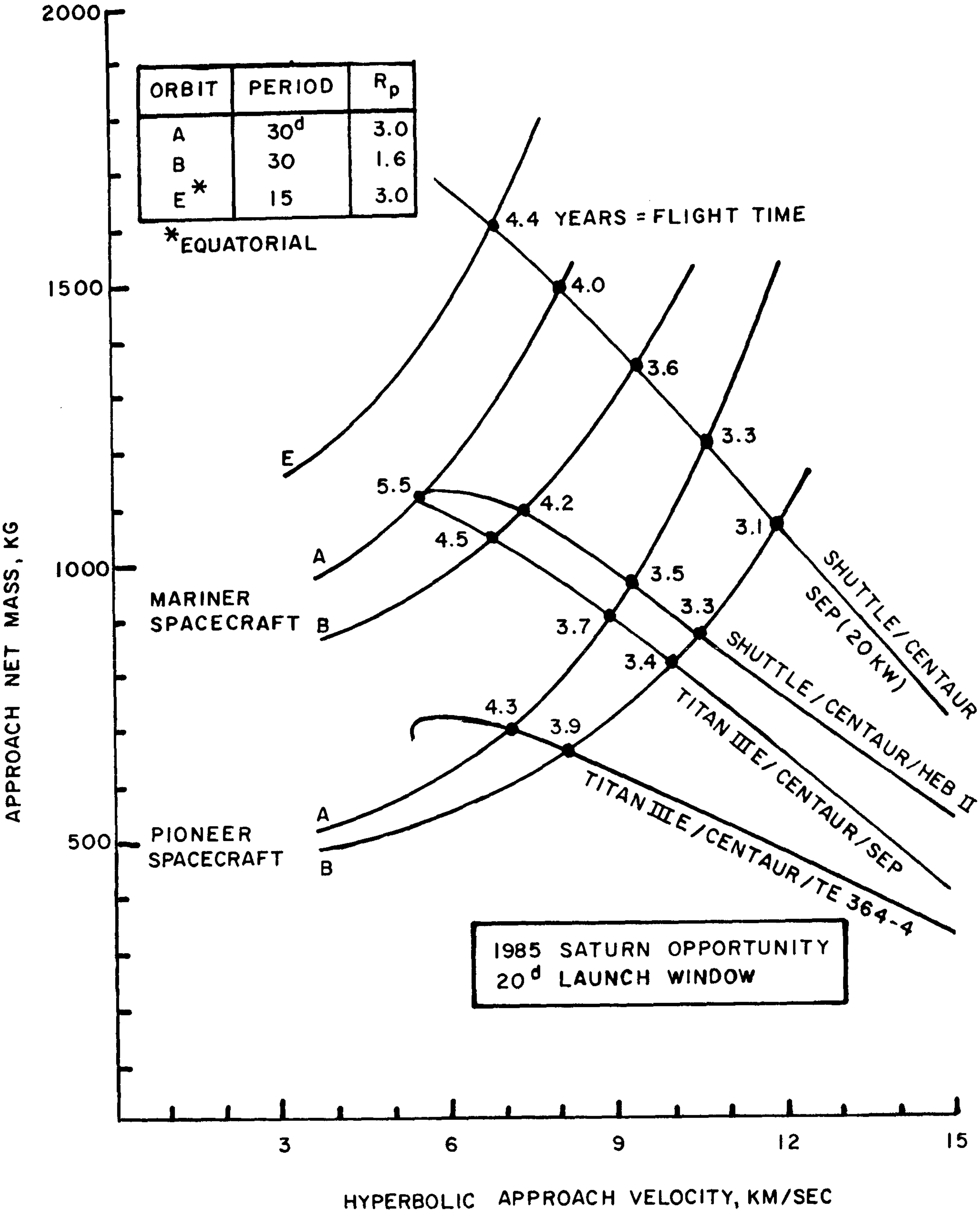

FIGURE S-2 SPACECRAFT REQUIREMENTS AND LAUNCH VEHICLE PERFORMANCE.

of putting the nominal Mariner spacecraft into the 3.0 R_s periapse orbit. Using the Shuttle/Centaur/SEP (20 kw) vehicle and allowing a total of 900 kg for the SEP stage which is jettisoned before orbit capture, the flight time is 4.0 years. Even for an equatorial orbit the flight time is 4.4 years. The flight times are independent of launch opportunity.

The obvious differences between Saturn and Jupiter orbiter missions are: 1) a five-year mission rather than three years, 2) a typical communications distance of 10 AU rather than 5 AU which makes the date rates differ by a factor of 4, and 3) a significantly larger launch vehicle. The longer lifetime requirement is less significant for the Mariner spacecraft while the Pioneer needs improvements in several key subsystems to qualify as a Saturn orbiter. These changes would also be beneficial for a Pioneer Jupiter orbiter.

Most of the instruments which have been selected for the Saturn orbiter payloads could also be used at Jupiter. The data rate difference will affect the operation of the imagery system and perhaps the design of its optics. The higher infrared flux from Jupiter means it would be easier to design an IR spectrometer for use only in Jupiter orbit. The micrometeroid detector could be dropped from consideration at Jupiter.

Attempts to improve our knowledge of Saturn's rings, magnetic field and radiation belts prior to the MJS '77 flyby are recommended as a method of permitting earlier final design work for an orbiting spacecraft. Assuming that the Shuttle upper stage and its operating characteristics will permit it, the Mariner spacecraft is more attractive. It would make sense to use two spacecraft so that all the candidate instruments can be utilized. The first would have payload #1 and go into the 3.0 R_s periapse orbit which encounters Titan. On the second spacecraft room would be made for fields and particles instruments by dropping some instruments from payload #1, such as the IR spectrometer. This spacecraft should be placed in the minimum periapse orbit.

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SATURN ORBITER MISSION STUDY

1. INTRODUCTION

This report provides a preliminary analysis of all the important aspects of missions which orbit Saturn. Orbiter missions to the outer planets, primarily Jupiter and Saturn, can be considered seriously in the 1980's. At that time data will already have been obtained from the Pioneer 10/G and Mariner Jupiter-Saturn '77 flyby missions. Atmospheric probes to the outer planets are also currently planned for the 1980's. Orbiters can provide data to complement and extend that obtained from flybys and atmospheric probes. The orbital mode is particularly advantageous for measurements of global circulation patterns and the dynamics of the magnetosphere, both of which require long term monitoring. In addition, Saturn has its unique ring system and the satellite Titan which has an atmosphere.

Previous studies (IITRI/Astro Sciences 1970, JPL 1971 and NASA/Ames 1971) have looked at Jupiter orbiters and established the basic requirements and characteristics of such missions. The current effort will use some information from these studies and the results will be compared. Specific aspects of Saturn missions have been studied before and these results were applied to this effort. From the work of Friedlander and Brandenburg (1970), it was known that Saturn orbiter missions required both a longer flight time and a larger launch vehicle, such as a Titan III E/Centaur/SEP. The advent of the Shuttle, however, calls for a new look at both chemical and low-thrust performance for Saturn orbiter missions. Some guidelines on the selection of instruments and orbits which optimized studies of Saturn's rings were established by Wells and Price (1971). There was no effort to integrate ring objectives with atmospheric, magnetospheric and satellite exploration. A very useful review of observational and theoretical work on the outer planets was written by Newburn and Gulkus (1971). The reports of the Science Definition Teams for MJS '77 included descriptions and justifications for potential instruments. These team reports and data on the Mariner spacecraft were attached to the MJS '77 AFO (NASA/OSS 1972a).

The overall objective of this study is to determine the requirements and operational characteristics of the early orbital missions of Saturn. The specific objectives are:

1. Briefly describe the Saturn system, select scientific objectives and relate them to orbital measurement techniques.

2. Describe appropriate instrumentation.

3. Characterize the options for orbit selection.

4. From an analysis of the demands on spacecraft subsystems determine the required spacecraft mass.

5. Evaluate both ballistic and low-thrust solar electric trajectories to determine launch vehicle requirements.

6. Recommend a preferred first-generation program for orbital investigation of the Saturn system and identify problems requiring further study.

The organization of the study follows from this list of objectives; one section per objective. Since Newburn and Gulkis (1971) have done a general review of the current scientific knowledge about Saturn, Section 2 concentrates on material which is useful for evaluating the performance of candidate instruments and for selecting of orbits. In Section 3, the measurement objectives are used to define instruments most of which are derived from currently available devices. Support requirements are given for science payloads placed in both inertial and spin stabilized spacecraft. The restrictions that the rings of Saturn and the radiation belts, if they exist, place on the selection of orbits are discussed in Section 4. Then the sensitivity of instrument performance to orbit selection is considered and illustrated for a typical arrival date in 1989. In Section 5, Mariner and Pioneer class spacecraft are described which, with appropriate changes from the current designs will meet the requirements for Saturn orbiter missions. Both ballistic and solar electric trajectories are investigated in Section 6 and payloads are found for the current Titan and the proposed Space Shuttle launch vehicles. The launch opportunities in 1980, 1982 and 1985 are studied and cover the range in ballistic trajectory performance for the 1980's. Section 7 summarizes the important conclusions and recommendations of this study, including a baseline program for Saturn orbiters and a comparison with Jupiter orbiters.

2. CURRENT SCIENTIFIC KNOWLEDGE

In some ways Saturn and Jupiter are sister planets; specifically in radius, rotation rate and banded appearance. However, there are significant differences in that Saturn has a ring system and its satellite system is dominated by a single body, Titan, which even has its own atmosphere. There probably are also significant differences in the internal structure, atmosphere, and magnetosphere of these two giant planets,making the study of both of them necessary and rewarding.

The material in this section is not intended to be a comprehensive review of current data and theories about Saturn. A familiarity with the observed and expected phenomena is, however, essential for the selection of mission objectives, the correlation of measurement techniques with objectives and the design of candidate scientific experiments.

2.1 General Properties

Table 2-1 lists some basic properties of Saturn and Jupiter taken from Newburn and Gulkis (1971). While the radii are similar, Saturn's mass is less than one third that of Jupiter and the calculated density is half as large. The low density plus the larger oblateness of Saturn has made it difficult to construct models of the interior. Improvements in describing the gravitational field, including separating the ring effects, and the shape of Saturn can be made with measurements of orbital perturbations and occultations and would aid in modeling the interior. Some information about conditions in the interior may come from nagnetic field measurements, a new determination of the excess amount of thermal radiation and a good model for the vertical structure of the observable atmosphere.

TABLE 2-1

PHYSICAL AND MECHANICAL PROPERTIES

PARAMETER	JUPITER	SATURN
MASS (EARTH = 1)	317.89	95.18
RADIUS (KM)	70,850	60,000
OBLATENESS	1/16.4	1/9.3
MEAN DENSITY (G/CM^3)	1.36	0.70
BOND ALBEDO	0.45	0.61
EFFECTIVE TEMPERATURE		
PREDICTED (°K)	105	71
OBSERVED	134	97
ROTATION PERIOD	$9^h\ 55^m$	$10^h\ 14^m$
INCLINATION OF EQUATOR TO ORBIT	3.07°	26.74°

2.2 Saturn's Atmosphere

Many earth-based observations have been made of the properties of the atmosphere. The basic problem of working under the earth's atmosphere limits the spatial resolution on Saturn to about 3,000 km, corresponding to half an arc second at mean opposition. With this resolution it has been possible to determine that Saturn's atmosphere is divided into bands which are as narrow as 5° of latitude or 5000 km (Reese 1971). Typical locations of features are given in Figure 2-1 (see also Figure 2-4). Additional dark bands (or belts) have been observed in the polar region and in the center of the equatorial zone. The latitudes of these bands have been relatively stable through the years despite the 26.74° inclination of Saturn's equator with respect to the ecliptic. The contrast between adjacent belts and zones is probably not more than 2:1 and in some spectral bands may be much less. Colors are at best subtle. A key goal of spacecraft observations must be to achieve better resolution of the global circulation pattern and horizontal structure of the atmosphere.

Small spots have been infrequently observed on Saturn. The spots shown on Figure 2-1 are typical locations of spots observed in the last 100 years. None have been as large or as permanent as Jupiter's Great Red Spot. Poor spatial resolution and low contrast may have accounted for the small number of events. Even so, the rotation periods deduced from the spot observations for Saturn's equatorial zone and belt are about 20 min. less than for the temperate regions. This is a wind shear of 1400 km/hour and some observations near the contact of belts and zones should be made to determine the relative motion. The observations of a white spot from October 1969 to February 1971 (Reese 1971) show that there was a damped sinusoidal component to its location. Similar studies of even smaller

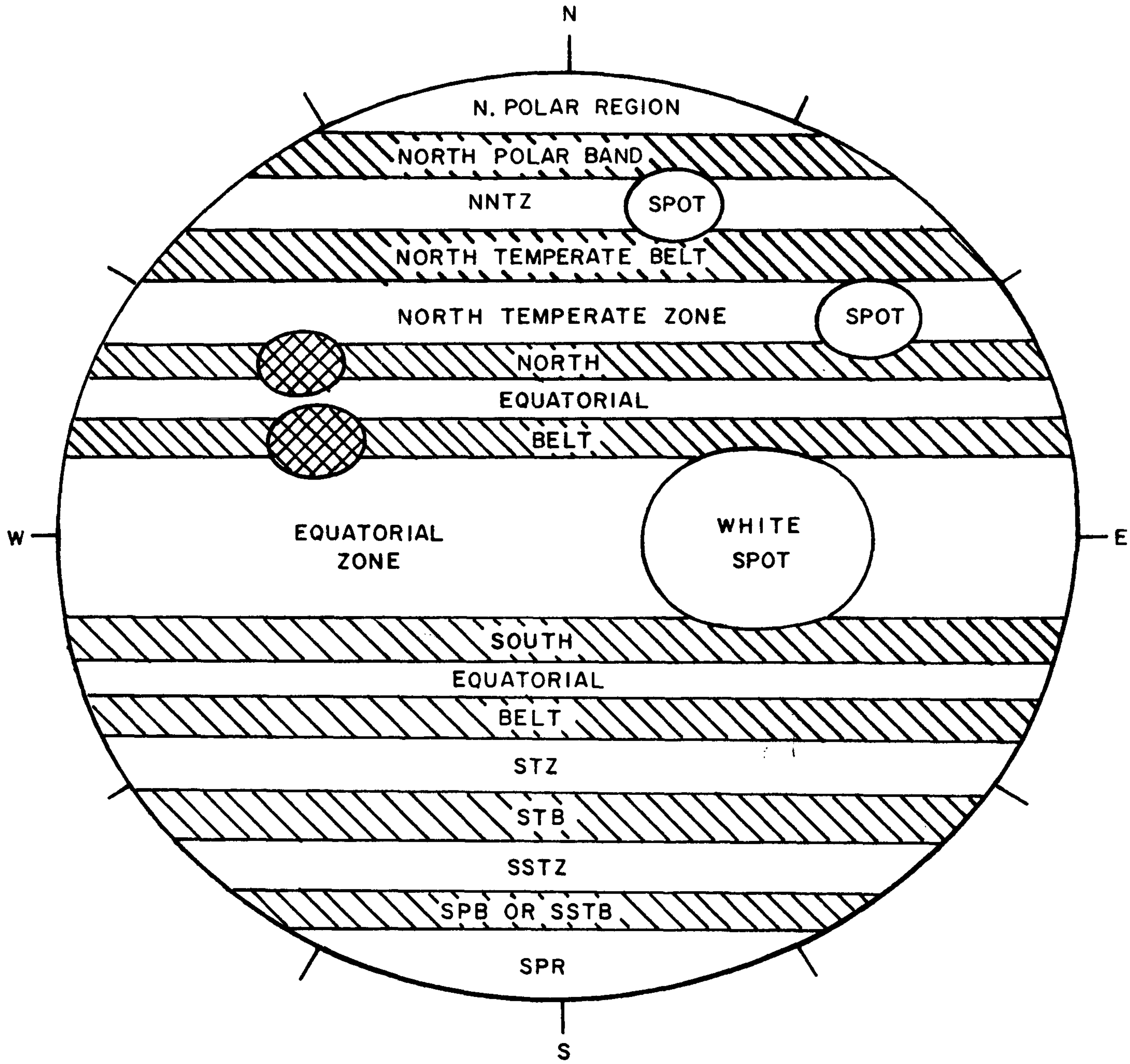


FIGURE 2–1 NOMENCLATURE FOR FEATURES ON SATURN'S GLOBE

local disturbances can be carried out from an orbiter mission which lasts for a year or more. It would also be desirable to obtain images of active areas which have dimensions of less than 10,000 km.

Two very important aspects of the atmosphere are its composition and its vertical structure. The known constituents are molecular hydrogen, methane and ammonia with H_2 by far the most abundant. Spectroscopic measurements, particularly in the far UV and the near IR, may reveal new molecules, but in general this is the work of an atmospheric probe. The orbiter can, however, provide useful data on the variation of composition between various regions.

The observed temperature of the atmosphere is $97 \pm 3°K$. Since Saturn's atmosphere is thick, only small temperature variations are expected. The corresponding thermal flux and the incident solar flux are compared in Figure 2-2. The reflected light is found by multiplying the incident flux by the albedo and the cosine of the incident angle. The thermal flux observed is about three times that expected,based on a calculation of the absorbed solar flux. Somewhat higher effective temperatures are observed near 5 μm (125°K) and at microwave wavelengths (about 180°K at 10 cm). At these wavelengths the contribution to the total emitted flux is very small and the higher temperatures probably indicate that the radiation comes from a deeper level in the atmosphere. Again, an atmospheric probe is the best way to study the vertical structure of an atmosphere since it can measure all the relevant parameters: temperature, pressure density, and composition. An orbiter is useful for extending these results in space and time. Useful techniques for obtaining some vertical profile information are occultations of the spacecraft radio signal and the inversion of spectral line profiles such as is done with CO_2 absorptions from earth

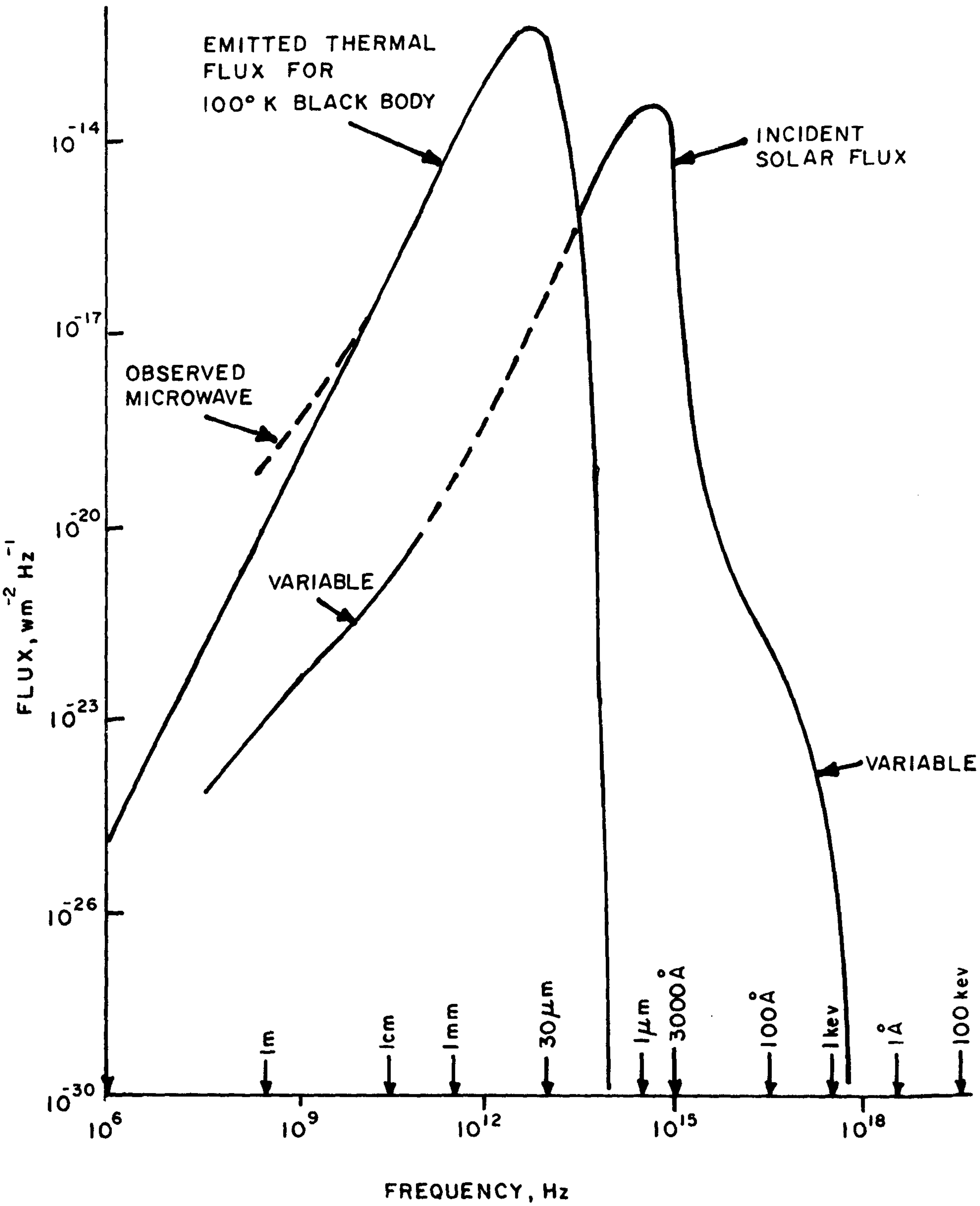


FIGURE 2-2. INCIDENT SOLAR AND EMITTED THERMAL RADIATION.

orbit. Aerosols and clouds are also part of the vertical structure problem and their presence will be indicated by their light scattering properties.

2.3 Saturn's Magnetosphere

There is no positive evidence for a magnetosphere around Saturn. It has been estimated that less than 10 percent of the observed microwave emission could be derived from synchrotron radiation by trapped electrons in a magnetic field. Nor are there strong radio bursts like those from Jupiter. (For a general view of the situation at Jupiter, see Beck 1972.) Nevertheless, the general similarity of these two large planets suggests that the mechanism producing Jupiter's strong field, about ten gauss at the surface, is operating at Saturn too. The solar wind would be the likely source of radiation belt particles. Therefore it will be assumed that the model for Jupiter developed by Divine (see Beck 1972) is a good approximation to the situation at Saturn. Figure 2-3 shows the flux and energy of the trapped particles in this nominal model as a function of magnetic shell parameter (L, the radius at which a field line crosses the magnetic equator). Because of the rings, fluxes are zero for $L > 2.3$, but this region could be larger if the magnetic poles are not near the geographic poles or if the rings are more extensive. This region would normally contribute a major fraction of the radio emission. Thus, at this time, the existence of a strong magnetic field and of radiation belts exterior to the rings cannot be disproved. Indeed, Haffner (1971) has shown that the synchrotron emission from a similar population of electrons at Saturn is less than 10 percent of the thermal microwave energy and thus in agreement with observation.

The exploration objectives are to describe the magnetic field, the fluxes, energies and pitch angle distribution of

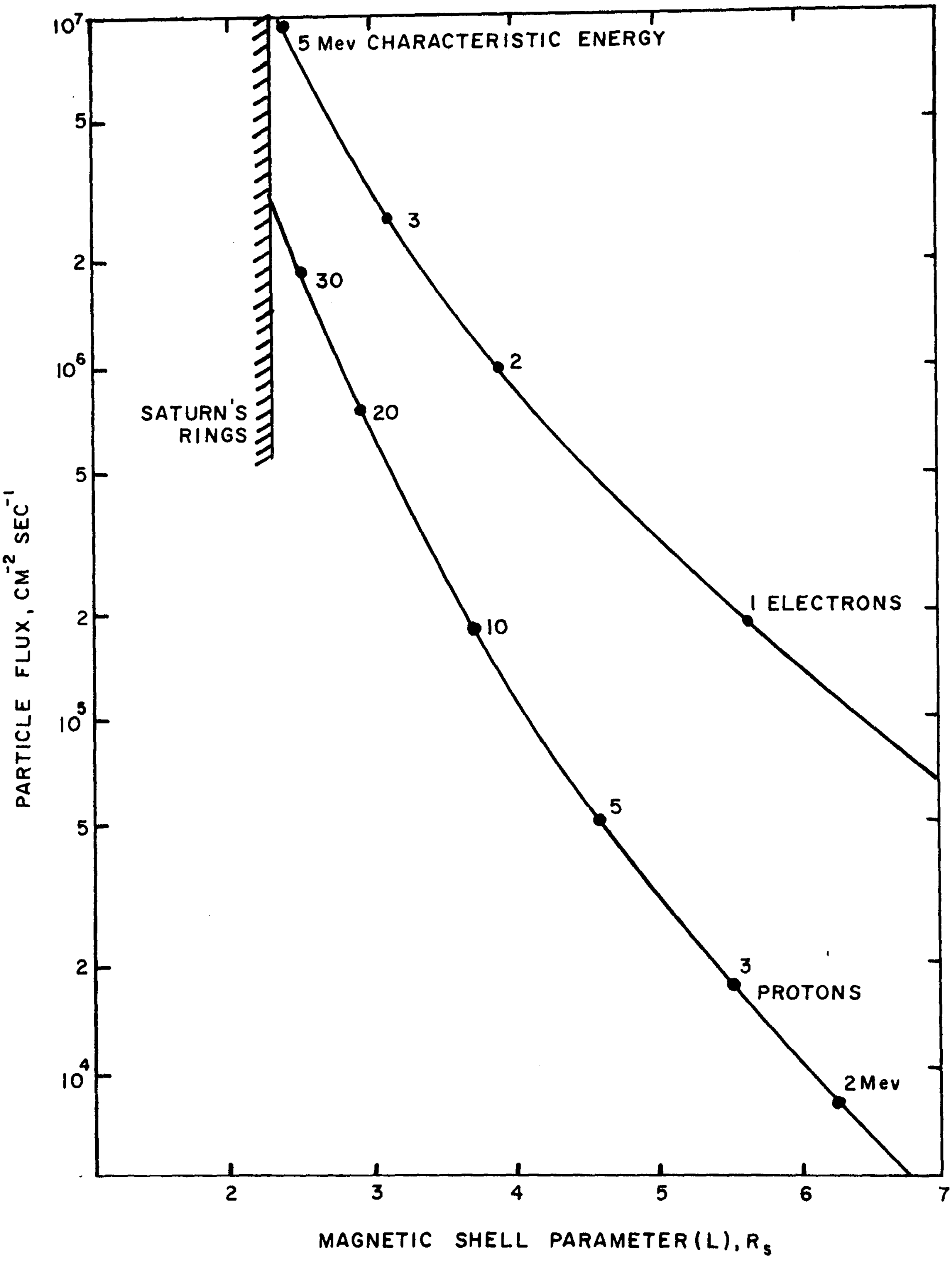


FIGURE 2-3 NOMINAL RADIATION BELT PARTICLE FLUXES

trapped particles and the interaction of the solar wind with Saturn's magnetosphere. Both the direct techniques for measuring magnetic fields and energetic particles and the indirect ones for measuring the radio waves should be used.

2.4 The Ring System

The ring system around Saturn is one of the most striking features in the solar system. Earth-based observations have demonstrated that the rings are confined to the equatorial plane, the particles moving in near circular orbits, and are not more than several kilometers thick. Three rings are well established, see Figure 2-4.

Rings A and B are somewhat brighter than Saturn's disc while ring C which presumably has a lower surface density of particles is not visible in this photograph. The possibilities for particles outside the classical rings are discussed in Section 4.1. Infrared observations of the rings show that ice is present and that the particles are in thermal equilibrium. But in general, there is insufficient data about particle sizes, spatial distribution and composition to devise a model for the evolution and thus origin of the ring system. The potential relationship between the formation of the ring system and the solar system has been noted by many, particularly Alfven.

According to Wells and Price (1971) the best techniques for study of the rings from orbit are photopolarimetry, radiometry and radio occultation. It is especially important to obtain photometric data over the complete range, 0 to 180°, of phase angles. Infrared and microwave observations of ring particles during and after their eclipse by Saturn could be very useful. Other methods, such as infrared spectroscopy and impact mass spectroscopy, should be considered since they offer the best chance of determining the composition of the ring material.

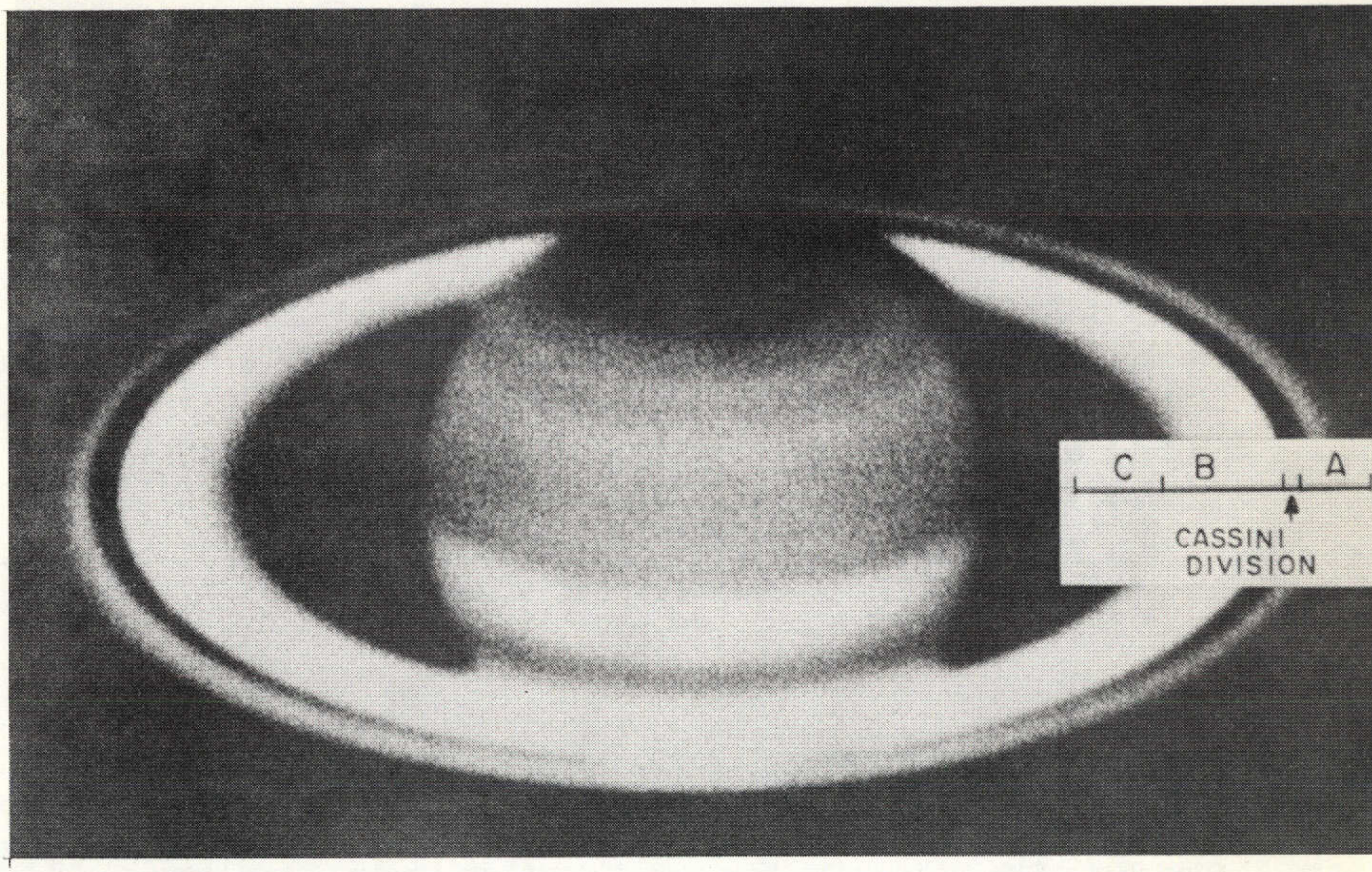


FIGURE 2-4

DIMENSIONS OF THE SATURN RING SYSTEM

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

* EQUATORIAL PLANET RADIUS R = 60,000 KM

2.5 The Satellites

Saturn has ten known satellites whose basic properties are listed in Table 2-2. Most can be classified as regular satellites because their orbits are prograde, circular and equatorial. Phoebe violates all three criteria and probably has been captured. Note that there are three orbit resonances; the periods of Tethys and Dione are twice those of Mimas and Enceladus, respectively, and Hyperion's is 4/3 times the period of Titan. The orbit of Janus us uncertain and an analysis of the four observations by Franklin et al. (1971) gave a semi-major axis of 2.82 R_s and a 0.815^d period.

Physically Titan dominates the satellite system. It is as large as the Galilean satellites. Titan is the only satellite in the solar system which has an appreciable atmosphere. It contains hydrogen and methane, but their abundance relative to the total is unknown. Recent infrared observations (Murphy et al. 1972) show that the large amplitude light curve of Iapetus is the result of the trailing side having an albedo of about 0.28 while for the leading side it is 0.04. The higher albedo of the satellites inside Titan's orbit and of the trailing side of Iapetus has been attributed to ice and the lower albedoes to rock. Except for Titan and Dione, the calculated densities are near unity although the errors are often large. This implies interiors of ice rather than rock. Lewis (1971) expects Titan to have a silicate core, a liquid water mantle and a thin crust of ices.

The study of Saturn's satellites can be advanced significantly by using an orbiting spacecraft to obtain close encounters with as many satellites as possible. The basic objectives are to look for surface features, determine the surface composition,

TABLE 2-2

SATELLITES OF SATURN: PHYSICAL DATA

	SATELLITE	MASS, 10^{21} kg	DIAMETER, km	DENSITY, g/cm^3	MAGNITUDE, V	ALBEDO
X	JANUS	-	(250)[1]	-	>13.5	(0.73)[2]
I	MIMAS	0.038 ± 0.001	(470)	-	12.1	(0.73)
II	ENCELADUS	0.085 ± 0.028	550 ± 300	~ 1.0	11.8	0.73
III	TETHYS	0.648 ± 0.017	1200 ± 200	0.7	10.3	0.61
IV	DIONE	1.052 ± 0.034	820 ± 400	~ 3.6	10.4	1.12
V	RHEA	~ 1.7	1300 ± 300	~ 1.5	9.8	0.83
VI	TITAN	137.6 ± 1.1	4850 ± 300	2.3	8.4	0.21
VII	HYPERION	-	(335)	-	14.2	(0.21)
VIII	IAPETUS	1.42 ± 0.74	1300 ± 400	~ 1.2	11.0	0.26
IX	PHOEBE	-	(100)	-	16.8	(0.21)

1. CALCULATED FROM MAGNITUDE AND ALBEDO
2. ASSUMED ALBEDO

SATELLITES OF SATURN: ORBITAL DATA

	SATELLITE	SEMIMAJOR AXIS, KM	SEMIMAJOR AXIS, R_s	ECCENTRICITY	INCLINATION	PERIOD, DAYS
X	JANUS	160,000	2.67	~0	~0	0.749
I	MIMAS	185,800	3.10	0.0201	1°31.0'	0.942422
II	ENCELADUS	238,300	3.97	0.00444	0°01.4'	1.370218
III	TETHYS	294,900	4.92	0	1°05.6'	1.887802
IV	DIONE	377,900	6.30	0.00221	0°01.4'	2.736916
V	RHEA	527,600	8.79	0.00098	0°21'	4.517503
VI	TITAN	1,222,600	20.38	0.029	0°20'	15.945452
VII	HYPERION	1,484,100	24.74	0.104	(17-56')	21.276665
VIII	IAPETUS	3,562,900	59.38	0.02828	14.72°	79.33082
IX	PHOEBE	12,960,000	216.00	0.16326	150.05°	550.45

and improve the basic physical data. The most important techniques for these objectives are imagery, spectroscopy and radio tracking.

Table 2-3 is presented here as a convenient summary of the objectives of Saturn exploration and the measurement techniques which are potentially useful for acquiring data to meet each objective. Whether a particular instrument will in fact be useful will depend upon its final design and on the orbit which is selected. For example, the last two techniques, radar/laser and sample analysis, were identified by Wells and Price (1971) as useful for ring investigations only from circular orbits near the ring plane.

EXPLORATION OBJECTIVES / MEASUREMENT TECHNIQUES	RADIO TRACKING	RADIO OCCULTATION	RADIO (LF) DETECTOR	μW RADIOMETER	IR IMAGER	IR SPECTROMETER	IR RADIOMETER	UV-VIS IMAGER	UV-VIS SPECTROMETER	UV-VIS PHOTOMETER	UV-VIS POLARIMETER	X-RAY IMAGER	CHARGED PART. DET.	MAGNETOMETER	MICRO-METEOR. DET.	RADAR/LASER	SAMPLE ANALYSIS
THERMAL STATE				●	●	○	●			●							
BODY STRUCTURE	●	○												○		○	
ATMOSPHERE:																	
COMPOSITION		○		○		●	○	○	●	○							
STRUCTURE-HORIZ.				○	○	○	○	●		○	○					○	
STRUCTURE-VERT.		●		●		●	○		●		○					○	
ACTIVITY					○	○		●	○								
IONOSPHERE			○	○					○	○		○				○	
MAGNETOSPHERE			●									○	●	●			
RINGS:																	
SURFACE DENSITY		●			○	○	●	●	○	●					●	○	
PARTICLE SIZE		●			○	●	●	○	●	●	○				●	●	●
COMPOSITION		○			○	●	○	○	●	○					○	○	●
THICKNESS, FLATNESS								●							●	●	
SATELLITES:																	
SURF. FEATURES					○			●		○						○	
COMPOSITION					○	●		○	●	○						○	
BODY STRUCTURE	●							●					○	●			
THERMAL STATE				○	●	○	●			●							
ATMOSPHERES (?)		●			○	●		○	●	○						○	

● VERY USEFUL

○ SOMEWHAT USEFUL

TABLE 2-3. OBJECTIVES AND TECHNIQUES FOR SATURN EXPLORATION.

3. CANDIDATE SCIENCE INSTRUMENTS

The time frame for the launch of a Saturn orbiter would probably be in the mid-1980's. This is after the flybys by MJS-77 for which instruments are currently being selected. It would be advisable, but not mandatory, that the final selection of orbiter instruments be made after the flyby results are known. As explained in Section 2.2, atmospheric probes and orbiters are complimentary. If the results of a probe mission were available at the time the orbiter is being designed, which seems unlikely, refinements could be made in the specifications for the orbiter instruments. However, for the purpose of this study, candidate instruments must be described and then selected for nominal payloads without the benefit of knowing what the MJS-77 payload is. The results of the MJS-77 Instrument Definition Teams were available as part of the AFO (NASA/OSS 1972a).

There are some instruments that can be excluded from consideration by orbit constraints. Detectors for in-situ analysis of the rings (Wells and Price 1971) require a circular orbit which is far beyond the capability of launch vehicles in the 1980's. Because of the rings, an orbit which skims through the upper atmosphere is not possible. This eliminates instruments similar to those on the Atmospheric Explorer (e.g., mass spectrometer, retarding potential analyzer). In any event, a skimmer orbit is not a substitute for atmospheric probe missions which are also being considered for the 1980's. No consideration was given to instruments which are used primarily for interplanetary measurements. Examples are cosmic ray telescopes and solar wind plasma detectors. Because the emphasis is on planetary studies, the selected payloads for Saturn orbiters should be different from the MJS-77 one.

Although orbits have not yet been selected, a little knowledge of the possibilities is required at this time. Energy requirements dictate the use of elliptical orbits with periods of about 15 to 30 days which have apoapses between 40 and 65 Saturn radii. Minimum altitudes of 0.6 to 3.0 R_s will be considered, but wherever possible an instrument should be designed to work over a wide altitude range. Each technique will now be discussed in the same order as in Table 2-3 and the instruments are summarized in Table 3-3.

3.1 Radio Frequency Techniques

This radio tracking and radio occultation experiments do not require any specific scientific instrumentation. Rather, the S- and X-band signals from the spacecraft are monitored carefully. Specific characteristics studied are (1) range and range-rate data, which determine the spacecraft's motion around the planet and permit study of the planet's gravitational field and satellite masses and (2) the attenuation characteristics of the signal as the spacecraft passes over the limb or behind the rings, which is extremely valuable for studying the atmospheric, ionospheric and ring structure. Such measurements should definitely be performed with respect to a Saturn orbiter. The techniques for atmospheric study would be roughly analogous to those used on previous Mariner missions. The maximum depth of several atmospheres is limited by critical refraction. Some improvements which were under consideration for MJS-77 would be very desirable. They are monopulse feed system, a radiometer channel and optional linear polarization which are best obtained through a redesign of the radio system which even reduces its weight (see Section 5).

Synchrotron emission from energetic electrons in the radiation belts and plasma wave emissions are expected if there are radiation belts. From the earth these signals are either blocked by the ionosphere or are too weak. The frequency ranges 15 kHz to 22 MHz and 10 Hz to 200 kHz were selected by the MJS-77 teams for a combined radio astronomy and plasma wave experiment. The experiments share crossed dipole antennas for E waves (10 m each) and a stepping radio frequency receiver. The plasma wave portion also has four additional receivers and a loop antenna for B waves. Considerable experience has been gained with similar instruments near the earth (Radio Astronomy Explorer, Orbiting Geophysical Observatory). Together the estimates for weight, power, and data rate are 7 kg, 10 w and 200 bps.

The longer the wavelength of microwave radiation, the less its absorption in outer planet atmospheres. Therefore measurement of microwave flux as a function of wavelength can indicate the atmospheric temperature as a function of atmospheric depth. From the earth such measurements generally have large errors and may also contain some signal from the rings and synchrotron emission. One NH_3 absorption feature ($\sim$1 cm) has been studied, but otherwise earth-based measurements have not provided spectroscopic information.

A spacecraft instrument might be useful for studying the thermal properties of the atmosphere, rings and satellites. Unfortunately microwave measurements have not been seriously considered for outer planet missions, so there is little information on what can actually be accomplished. There are three possible reasons why this has happened. First, the atmospheric structure can also be studied by infrared spectroscopy and radio occultations. To get even crude spatial resolution, say 10,000 km, from an altitude of 3 R_s requires a FOV of 3° and an antenna diameter of 22 times the wavelength. Even for a main communications antenna with a diameter of 3.4 m, this means wavelengths of 15 cm or less. Finally, the current instruments flying on Nimbus spacecraft in low earth orbit are rather heavy — 20 to

30 kg. However, there appears to be no reason why a 10 kg multi-frequency microwave spectrometer could not be constructed for a Saturn orbiter mission (D. H. Staelin, private communication). With a multi-frequency receiver it is possible to correct the measured temperatures for observed molecular absorptions. According to Klopp (1969) the minimum integration time per measurement is about 0.1 sec for a temperature resolution of 1°K. Because of the uncertainties about microwave instruments, one is not included in the list of candidate instruments, however further study would be very desirable.

3.2 Infrared Techniques

In the infrared bodies emit thermal radiation. Figure 2-2 shows the flux from a 100°K blackbody which is typical of that expected from Saturn's atmosphere and the illuminated portions of the satellites and rings. The peak flux occurs at a wavelength of about 30 μm. The shaded portions of the rings are expected to be colder, say 60°K, so the infrared emission will peak at about 60 μm. One important objective is to measure the far infrared flux to determine temperatures as functions of location, illumation conditions and time. For this purpose a scanning radiometer is needed. A second objective is to determine the atmospheric structure and composition by studying the infrared spectrum of both thermal and reflected solar radiation. Spectrometers and in particular a Fourier interferometer will be discussed later.

Infrared radiometers have been frequently used on planetary missions. The basic design, as described by Chase (1969),is an antimony-bismuth junction detector onto which energy in a selected band is focused. Calibration is provided by viewing deep space and an internal reference. The instrument which is proposed here for a Saturn orbiter is based on the

TABLE 3-1

INFRARED INSTRUMENTS

Symbol	Quantity	Units	IR Radiometer:		IR Spectrometer:		
			Channel 1	Channel 2	Option 1	Option 2	Option 3
A_d	Detector Area	m^2	1.0×10^{-6}	1.0×10^{-6}	2×10^{-5}	2×10^{-5}	2×10^{-5}
A	Telescope Area	m^2	1.8×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	1.8×10^{-2}
η	Optical Efficiency	-	0.5	0.5	0.1	0.1	0.1
D^*	Detector Figure of Merit	$mHz^{1/2}/w$	4.2×10^6	4.2×10^6	10^6	2×10^8	1×10^6
$\Delta\nu$	Frequency Resolution	Hz	6.4×10^{12}	2×10^{12}	6×10^{11}	1.5×10^{11}	1.5×10^{11}
Ω	Solid Angle	sr	7.6×10^{-5}	7.6×10^{-5}	6.8×10^{-4}	6.8×10^{-4}	6.8×10^{-4}
τ	Dwell Time	sec	0.017	0.017	13	13	13
NEP	Noise Equivalent Power	$w/(m^2 sec\ Hz)$	4.2×10^{-16}	1.3×10^{-15}	1.7×10^{-15}	3.4×10^{-17}	6.6×10^{-15}
F_{sig}	Signal	$w/(m^2 sec\ Hz)$	10^{-13}	10^{-14}	10^{-13}	10^{-15}	10^{-12}
T_b	Blackbody Temperature	°K	100	50	100°	sun	sun
S/N	Signal to Noise	-	240	7.5	60	30	150
FOV	Field of View	deg	0.5°	0.5°	1.5°	1.5°	1.5°
—	Wavelength Interval	μm	20-35	60-100	15-40	2-6	2-6
$\nu/\Delta\nu$	Spectral Resolution	cm^{-1}	-	-	20	5	5

Note: $NEP = A_d^{1/2} \left[A\ \eta\ D^*\ \Delta\nu\ \Omega\ \tau^{1/2}\right]^{-1}$

Pioneer 10/G device (Chase, private communication). Table 3-1 gives the basic data that are required to calculate the noise equivalent power, NEP, as defined by Hanel (1970). The two pass bands have been selected to be near the expected peaks for 100°K and 60°K respectively. The telescope has a 6 inch diameter or twice that of Pioneer 10/G. The field of view has been set at 0.5° which will provide 3000 km resolution from an altitude of about 6 R_s. Note that at the far infrared wavelength of 30 μm a five meter earth-based telescope is diffraction limited to about 10,000 km surface resolution. The 5 rpm spin rate of the Pioneer spacecraft gives a maximum dwell time 0.017 seconds for a 0.5° FOV. The length of time required to generate an "image" with 3000 km resolution is 8 minutes. Signals are taken from Figure 2-2. In either channel the signal to noise ratio for 100°K blackbodies is about 100 so that relative temperatures can easily be measured with an accuracy of 1°K or better. However, for surfaces as cold as 50°K only channel two is useful and the error will be about 4°K. The data rate corresponding to two 8 bit readings at 0.017 sec intervals is 1.0 kbps, but the average rate is not more than 100 bps. The weight is estimated as 4 kg with some allowance for the larger optics and the power as 4 watts.

Some modifications to this design would be needed when a Mariner class spacecraft is used. A scanning mechanism must replace the natural spin of the Pioneer. At the same time the dwell time could be increased by a factor of 10 without also changing the "image" acquisition time. The S/N ratios would then be about three times higher. Several options, such as higher spatial or spectral resolution or smaller optics, could be considered. The demands that a modified radiometer would place on the spacecraft would be about the same.

The MJS-77 infrared instrument definition team (NASA/OSS 1972a) proposed spectral studies either at 8 μm, a methane band, or near 25 μm where H_2 absorbs for temperature profiling of outer planet atmospheres. They suggested that with resolutions of about 20 cm^{-1} it would be possible to reconstruct temperature profiles over pressures from 0.01 to 1.0 bars with the methane line and from 0.1 to 1.0 bars with hydrogen. Higher resolutions, about 5 cm^{-1}, are needed to detect lines of new atmospheric constituents in the spectral band 2 to 6 μm. For instance CH_3D has been detected on Jupiter at 4.6 μm (Beer et al. 1972). Both dispersive and interferometer spectrometers have been used before (on Mariner 6, 7 and Mariner 9 respectively). The instruments discussed here will be interferometers which as explained by Hanel (1970, 1971) results in an improved signal to noise ratio in most applications. However, when information on a specific spectral feature is desired, it is often possible to obtain similar quality data with a multi-channel radiometer using interference filters (see MJS-77 team report). Three measurement options are presented: 1) the H_2 rotational spectrum, 2) trace constituents in the reflected solar spectrum and 3) trace constituents at solar occultation. The H/He ratio is also determined by the first option while the second case can be extended to include the 8 μm methane band.

In all three cases a 6 inch telescope, similar to and perhaps shared with the IR radiometer, has been assumed. The FOV has been set at 1.5° so that 3000 km resolution is obtained at 2 R_s, a typical orbit periapse. Most other parameters needed to calculate the noise equivalent power are identical to the values for Mariner 9. For option 2, the thermistor detector was replaced by a Pb-Se photon detector cooled to 195°K and which has a much higher sensitivity up to 6 μm. However, to make measurements near 8 μm requires another detector, possibly cooled Hg-Cd-Te, which would have a similar figure of merit. For case 3 the effective signal is found by dividing the solar flux at 6 μm by the telescope solid angle. In the first two cases, the signal to noise ratios are not so far below 100 that one should dismiss them as impractical. For the third option the signal to noise is high enough, but there is only one opportunity per orbit to make a measurement. The choice between these options is, perhaps, best left unresolved. In any case, the IR spectrometer or spectroradiometer is likely to have a mass of about 15 kg and require about 12 w of power. Depending on the option, the data rate could be as much as 1.0 kbps.

3.3 Visible and Ultraviolet Techniques

Close range visible imagery of an outer planet has never been performed. The data from Pioneer 10, which will encounter Jupiter in 1974, will be therefore especially interesting. Whereas high-resolution imagery of hard-surface planets, viz. Mars and the Moon, has made revolutionary contributions to our understanding of these planets, opinion is divided regarding how important (relatively) such imagery may be for gaseous planets. For example, beyond a certain resolution, the planet may merely appear hazy and reveal no detailed cloud structure. Results of high-resolution imagery of Venus on Mariner Venus-Mercury 1973 will be relevant. As stated in Section 2, it is expected that visual imagery will be important for studies of global atmospheric circulation and horizontal structure and for reconnaisance of the satellites.

Because our present earth-based resolution of Saturn is so low (about 3000 km), this study postulates that better spatial resolution would be useful. More specifically, plans should include either a television camera or a spin scan system which can provide significant coverage at surface resolutions of about 300 km. It will be apparent that providing continuous

Table 3-2

IMAGERY SYSTEMS FOR A SATURN ORBITER

PARAMETER	UNITS	TELEVISION	SPIN SCAN
Sensor type	--	Slow Scan Vidicon	10 Silicon Detectors
Spectral Range	μm	0.3 to 0.6	0.3 to 0.8
Focal Length	mm	300	600
Aperture Stop (f#)	--	2.35	4
Angular Resolution	μrad	45	100
Format	pixels	832	300
	lines	700	(300)
Field of View	deg	1.8 x 2.3	1.8 x 1.8
Exposure Time	msec	< 60	0.2
System Surface Resolution:			
at Apoapse (60 R_s)	km/ℓp[a]	330	700
at Periapse (3 R_s)	km/ℓp[a]	11	35
Data per Frame	10^6 bits	5.2	0.8
Frame Interval	min	0.6	6.0
Data Rate	kbps	130	2.2[b]
Weight	kg	15	12
Power	w	18	10

a-km per line pair

b-assumes data is buffered

coverage at higher resolutions is beyond the capability of the telemetry subsystem so higher resolution imagery systems, such as return beam vidicons and film, do not need to be considered.

Since the spacecraft spends most of its time in orbit near the apoapse, the visual imagery system should, if possible, be designed to work at 60 R_s, a typical apoapse altitude. As Table 3-2 shows this requires a 300 mm focal length lens for the Mariner 9 vidicon camera compared with focal lengths of 50 to 500 mm for the wide and narrow angle optics for Mariner 9 (Carr et.al. 1972). The minimum exposure time for the brightest scenes and without a filter is calculated to be 1.0 msec (see Klopp 1969). The maximum exposure time is determined by image smear. Normally the major component of relative motion is from Saturn's rotation, 10.3 km/sec at the equator, and the highest ground speed for orbits considered in the next section is about 30 km/sec. The maximum exposure time (0.06 sec) is found by allowing not more than 1.8 km of relative motion during the measurement. (Note: 1.8 km is one third of the resolution per TV line at periapse.) Using this maximum time will permit the use of blue, green and yellow filters for all exposures and red filters for the brightest scenes only. During satellite encounters the relative velocities are about 10 km/sec so that for bright scenes image smear will be a problem only for resolutions better than about 30 m. Color filter options may be somewhat restricted for satellite observations because their reflectivities range from 0.04 to unity. Since there is generally adequate time to make the desired exposures, it is not necessary to use an intensified vidicon (Viking) or a silicon intensifier vidicon (proposed for TOPS Grand Tour). The weight and power listed in Table 3-2 are for a single TV, but like other Mariner missions, the science payload will have two cameras. The MVM '73 arrangement of two identical narrow angle TV's with provision for a wide angle view through an auxiliary lens will be adopted here.

An analysis similar to that done for the infrared instruments shows that the multichannel spin scan camera described in Table 3-2 has a signal to noise ratio of about 100. The 0.2 msec exposure time is determined by the spin rate while the six minute image interval follows from the fact that thirty spacecraft revolutions are needed to generate 300 scan lines or a full disc view from 60 R_s. Its angular resolution is a factor of two less than the TV, representing a reasonable compromise in lens diameter and data rate so that the instrument is compatible with the Pioneer spacecraft. Color filters can be used if a lower signal to noise is accepted. The weight and power estimates are based on the ATS cloud cover experiment which is in many respects similar to this instrument.

A major difference between these two imagery systems is in data handling requirements. For the vidicon, the data readout rate is determined by the time the image can be retained on the camera face (the nominal Mariner value is 42 sec). Since it is not possible to provide a 130 kbps telemetry rate from Saturn, the best solution is to put the data onto tape for subsequent readout. A tape recorder is very useful when there is a large amount of interesting data to be collected in a short time such as satellite encounters and high resolution atmospheric coverage near periapse. Another useful feature would be reduced vidicon formats, say 416 x 350 which, as shown in Section 5, would permit real-time imagery. For the spin scan a buffer is required to take data from the instrument at 450 kbps (ten measurements each 0.2 msec) and to output at the rate of 2.2 kbps. This is possible because data is acquired during only 1.8° per spacecraft rotation. Since a larger data rate can be supported, a larger measurement arc can be used as the spacecraft gets nearer Saturn, up to 9° for the Pioneer spacecraft described in Section 5. The buffer capacity should be at least 0.15 million bits.

Besides visible imagery, accurate measurements of the absolute flux of visible reflected light are desired, primarily to measure albedo and compare with thermal emission. Here we suggest an instrument similar to the Pioneer 10/G photopolarimeter which consists of a one-inch optical telescope, a beam-splitting Wollaston prism (which splits the image into two mutually orthogonal polarized beams), two sets of coupling and filtering optics, and channeltron detectors. For the Saturn orbiter a similar instrument would be more than adequate. A single telescope with about five selectable filters between 0.3 and 0.8 μm (at three polarizations) and a field of view similar to the IR radiometer is desired. The buffered data rate would be about 50 bps or 60 measurements with one filter on each spacecraft revolution (or mirror movement).

The principal objective of the UV observations should be to measure the composition of the atmospheres of the outer planets. Emphasis was to be placed on hydrogen and helium, presumably the most abundant species in the atmospheres. Every effort should be made to provide a means of relating density profiles obtained in the upper atmosphere to the mixed region of the atmosphere. Airglow observations of H Lα and HeI 584 Å radiation off the bright limb would be useful at Saturn in giving H and He upper atmosphere densities. By observing the (Lyman β)H_2 fluorescence line, excited by a solar line in accidental resonance, the H_2 density may be tracked to the turbopause. Observation of the sun in the UV as it is occulted by the planet would be a useful tool to determine H, He, H_2 and perhaps other species in the atmosphere.

The preferred instrument for both airglow and occultation would be an objective grating spectrometer with an array of channel multiplier detectors in the focal plane. During close encounter the instrument would act as a multi-wavelength monochromator. The grating would be fixed and detectors set to observe, say 1216 Å, 584 Å, 1607 Å (the Lyman H_2 fluorescence), at either side of 504 Å, 805 Å and 918 Å, the absorption edges for He, H_2 and H and at other wavelengths set to map minor constituents like methane through the turbopause. Grating spectrometers have been used on Mariner 6,7 and 9 and are described by Pearce et al. (1972). For the MVM '73, however, a smaller instrument, very similar to the one desired, is being constructed which weighs 4 kg.

During the airglow observations of the limb the scale height can be measured if the angular resolution is high enough. But at the typical periapse radius of 3 R_s the range to the limb is 2.8 R_s, so that a field of view of about 100 μrad is required to match the expected 20 to 50 km scale height. The use of such a small FOV is not within the pointing accuracy and stability of a Mariner class spacecraft, even if the periapse radius can be reduced somewhat.

3.4 Fields and Particles Techniques

The range of magnetic fields which would be encountered by a Saturn orbiter are from about 3.5×10^{-6} to 2 gauss. The low value corresponds to the interplanetary field at 10 AU while the high one is expected if Saturn has the same magnetic moment as Jupiter. The Pioneer 10/G vector helium magnetometer is well suited to such measurements (for a general review of currently available magnetometers see Ness 1970).

Again, assuming that the expected Saturn's trapped energetic particles are similar to Jupiter's in flux and energy, then a judicious choice of techniques from Pioneer 10/G will allow all the important measurements to be made by a small (4 kg) unified experiment. Since such a wide variety of instruments are in use and none place large demands on the spacecraft, a detailed discussion of their characteristics is not necessary.

An interesting, although speculative instrument for a Saturn orbiter is an impact mass spectrometer to determine the composition of ring material. The measurements probably must be made outside the visible rings. Data on the elements from oxygen to iron should be obtained. High velocity impacts, typically 15 km/sec (Wells and Price 1971), will ionize the particles and the resulting ionized atoms can be analyzed in a time-of-flight mass spectrometer similar to that planned for HELIOS. From the total number of ions produced, a mass can be deduced since the impact velocity will be known. This instrument would have a mass of five kilograms, a power consumption of five watts, and, because of a low event rate, essentially zero for a data rate.

3.5 Candidate Science Payloads

The science payload for a three-axis stabilized spacecraft could include all of the instruments described above with the exception of the spin scan imager. Thus the maximum requirements for a Mariner class mission are a science weight of 77 kg, a power of 83 w and a 132 kbps data rate. Two factors, the number of instruments and their high power consumption relative to a spacecraft based on MJS-77 (see Section 5), make it desirable to look at science payloads with restricted capabilities. Payload #1 in Table 3-3 has been selected to emphasize atmospheric, satellite and ring measurements. This reduces the number of instruments by four and the power by 18 w. The television, the IR spectrometer and the UV spectrometer (for some measurements), which are included in payload #1, all need three-axis pointing control. Almost the same reduction in payload weight and power would accrue if only the IR spectrometer

Table 3-3

INSTRUMENTS FOR SATURN ORBITERS

Instrument	Weight (kg)	Power (w)	Data Rate (bps)	Payload #1	#2	Similar Instruments
TV system	30	36	130k	x	-	Mariner 9
Spin Scan	12	10	11k	-	x	ATS
Photopolarimeter	4	4	500	x	x	Pioneer 10
IR Radiometer	4	4	100	x	x	Pioneer 10
Radio Science	-	-	-	x	x	Viking
UV Spectrometer	4	4	100	x	a	Mariner '73
IR Spectrometer	15	12	1000	x	-	Mariner 9
Magnetometer	3	5	30	x	x	Pioneer 10
Charged Particles	5	5	30	a	x	Pioneer 10
Plasma Wave	4	5	100	a	x	OGO
Radio Astronomy	3	5	100	a	x	RAE
Micrometeoroid Detector	5	3	-	a	x	Helios
TOTAL-MARINER	60	65	132k	x	-	
	77	83	132k	all	-	
TOTAL-PIONEER	36	41	12k	-	x	
	40	45	12k	-	all	

x - selected

a - alternate

were dropped. This would be an attractive option to study the magnetosphere and the other areas if only a Mariner class spacecraft were available for Saturn orbiter missions.

The spin stabilized Pioneer spacecraft which is described in Section 5 can support payload #2. This payload includes the most important instruments for observations of the rings and the magnetosphere but its lower resolution imaging system and lack of spectrometers make it inferior to payload #1 for atmospheric and satellite measurements. The support requirements are a weight of 36 kg, 41 w of power and a buffered data rate of 12 kbps. All three are significant increases over the values for the current Pioneer 10/G spacecraft. However the changes that are made to the spacecraft subsystems to support this payload are reasonable.

4. OPTIONS FOR SATURN ORBITER MISSIONS

The orbit selected for an orbiter mission should take into account the environmental constraints, the scientific objectives and the capabilities of spacecraft and propulsion systems. In this section a set of orbit options is generated which reflects operational goals and constraints and which can be used in subsequent sections on spacecraft and trajectories.

4.1 Environmental Constraints

The ring system which lies in Saturn's equatorial plane is a definite hazard to an orbiting spacecraft. In a classical description, ring particles are found from 1.20 to 2.28 Saturn radii. Because particles in this region are closely spaced, they are a hazard even though little is known about their size distribution. A recent photograph obtained by Guerin (1970) shows an additional band of ring material from the surface out to 1.20 R_s. Feibelman (1967) has reported that there is also some material out to about 4 Saturn radii in photographs taken in 1966 when the earth was in Saturn's equatorial plane. However, with a brightness of not more than 15th magnitude per square arc second, this new ring is very sparsely populated (optical thickness of the order 10^{-7}). Thus when the particles are larger than one millimeter and a hazard to the spacecraft, the chance of being hit is small. There are a few visual reports of ring material exterior to the classical rings but inside the orbit of Mimas ($a = 3.10\ R_s$). The theoretical model of Franklin et al. (1971) predicts that two narrow rings are allowed in the radial range 2.4 to 2.7 R_s but with a maximum surface density well below that of the adjacent A ring.

While there is no conclusive evidence for a hazardous density of particles beyond 2.3 R_s, we feel that a nominal first mission should not cross the ring plane at less than 3.0 R_s.

To account for changes in the assessment of this problem, some missions could also be considered which cross the rings at 2.3 and 4.0 R_s.

Specifying a minimum radius at which a spacecraft may cross Saturn's equatorial plane in effect limits the choice of the periapse radius (R_p) and the argument of periapse (ω) of the spacecraft orbit. Any orbit with a periapse of 3.0 R_s or greater is allowed and an R_p = 1.6 R_s can be achieved by setting ω equal to 90°. However, for orbits with $1.6 < R_p < 3.0\ R_s$ it may be necessary to control the perturbations in the argument of periapse that are caused by Saturn's oblateness.

For reasons given in Section 2.3, calculations of the radiation damage to a Saturn orbiter will be made assuming that exterior to the rings radiation belt models for Jupiter are appropriate. The influences of both protons and electrons have been calculated by integrating the flux over one 30 day orbit with variable periapse radius. The results are useful on a per orbit basis for other orbit periods. As Figure 4-1 shows, the fluence peaks for orbits with a periapse of 2.3 R_s, the inside limit of the belts in this nominal model. The maximum doses are about 6×10^{10} electrons cm^{-2} $orbit^{-1}$ and 1.2×10^{10} protons cm^{-2} $orbit^{-1}$ with a nominal amount, 0.25 g/cm^2, of shielding.

Opinions vary over what is an acceptable level of radiation. The Pioneer 10/G spacecraft were designed for a proton fluence of about 10^{11} cm^{-2}, which meant that some transistor types which are adversely affected by 10^9 cm^{-2} were not used (NASA/Ames 1971). The nominal model predicts eight or more orbits are possible with this threshold. But the upper limit model for Jupiter (Beck 1972) would have a fluence about 2000 times the nominal. To satisfy this constraint would require a large orbit periapse and/or a higher component tolerance. Using a tolerance of

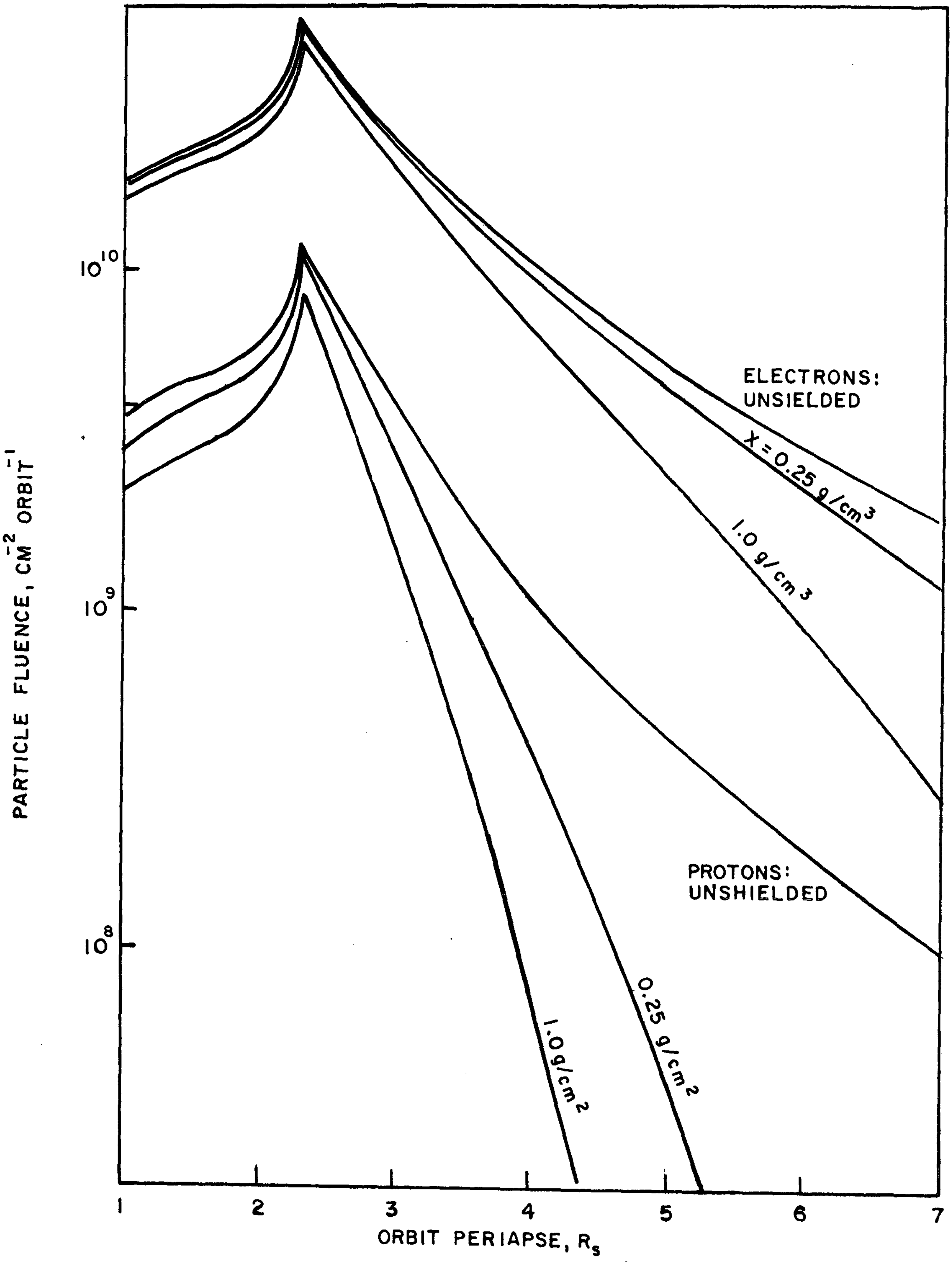


FIGURE 4-1 NOMINAL RADIATION BELT PARTICLE FLUENCES

3×10^{12} cm^{-2}, the level suggested by Divida (see Beck 1972) for the TOPS spacecraft, and 1.0 g/cm^2 allows a spacecraft with a periapse of 4 Saturn radii to survive 10 orbits.

In general, an electron damage threshold of 3×10^{12} cm^{-2} is less restrictive than a proton limit of 10^{11} cm^{-2}. At least 50 orbits may be completed before this electron fluence is exceeded. The difference between the nominal and the upper limit model for the trapped electrons could not be more than a factor of ten without violating the limit on the observed radio emission, so in all cases the primary constraint on spacecraft operation would be the proton flux. Note that to keep things simple, many factors which are of relatively minor importance have been ignored. Specifically, the shielding was assumed to be the same in all directions, the orbit was assumed to be in the magnetic equatorial plane and no corrections were made for the relative damage caused by particles of different energies. The last can increase predicted fluences for protons (by a factor of three or less) but in all other cases the actual flux would be less than values given here.

In summary, the radiation belt problem at Saturn is not likely to be worse than at Jupiter. In particular, an orbit with a periapse of 1.6 R_s is as safe as one with 3.0 R_s, thanks to the termination of the belts by the rings and a spacecraft can easily survive for at least ten orbits, the minimum acceptable number of orbits, if the fluxes are not greater than nominal. It will be necessary to use a 4.0 R_s periapse if the proton fluence is much larger than this prediction.

4.2 Selection of Candidate Orbits

The impact that the selection of an orbit has on the measurement objectives and instrument performance is the topic of this section. The order in which the major exploration areas will be discussed is satellites, rings, magnetosphere and finally the atmosphere. This order does not reflect relative importance.

In the previous section, it was determined that the periapse radius of candidate orbits should be greater than 1.6 R_s and that 3.0 and 4.0 R_s were particularly interesting values because the former could be free of restrictions on its angular orientation while the latter would significantly decrease the radiation dose received by the spacecraft from trapped protons. Periods of less than about 15 days result in too large a fraction of the approach spacecraft mass being devoted to propulsion. This will be discussed further in Section 5.

For the purpose of illustrations in this section, 22 February 1989 has been used as the arrival date for a 1500 day mission launched in 1985. The arrival velocity and the relative positions of the sun, the approach direction (VHP) and Saturn's equator are typical of those for orbiter missions in the 1982 to 1986 launch opportunity interval. Figure 4-2 shows possible locations of periapse in a Saturn centered inertial coordinate frame. Note that the inclination of a single impulse capture orbit cannot be less than the approach declination or in this case 22.6°. All are on the dark side of Saturn. However, for prograde orbits with an inclination of less than about 45° the periapse is near the morning terminator. For such orbits the apoapse will be near the evening terminator. The planes of two orbits which will be discussed frequently in this section are also shown in this figure.

Study of the satellites, especially high resolution (~ 100 m) surface imagery and radio occultations, requires that the spacecraft have close encounters with them. Seven of

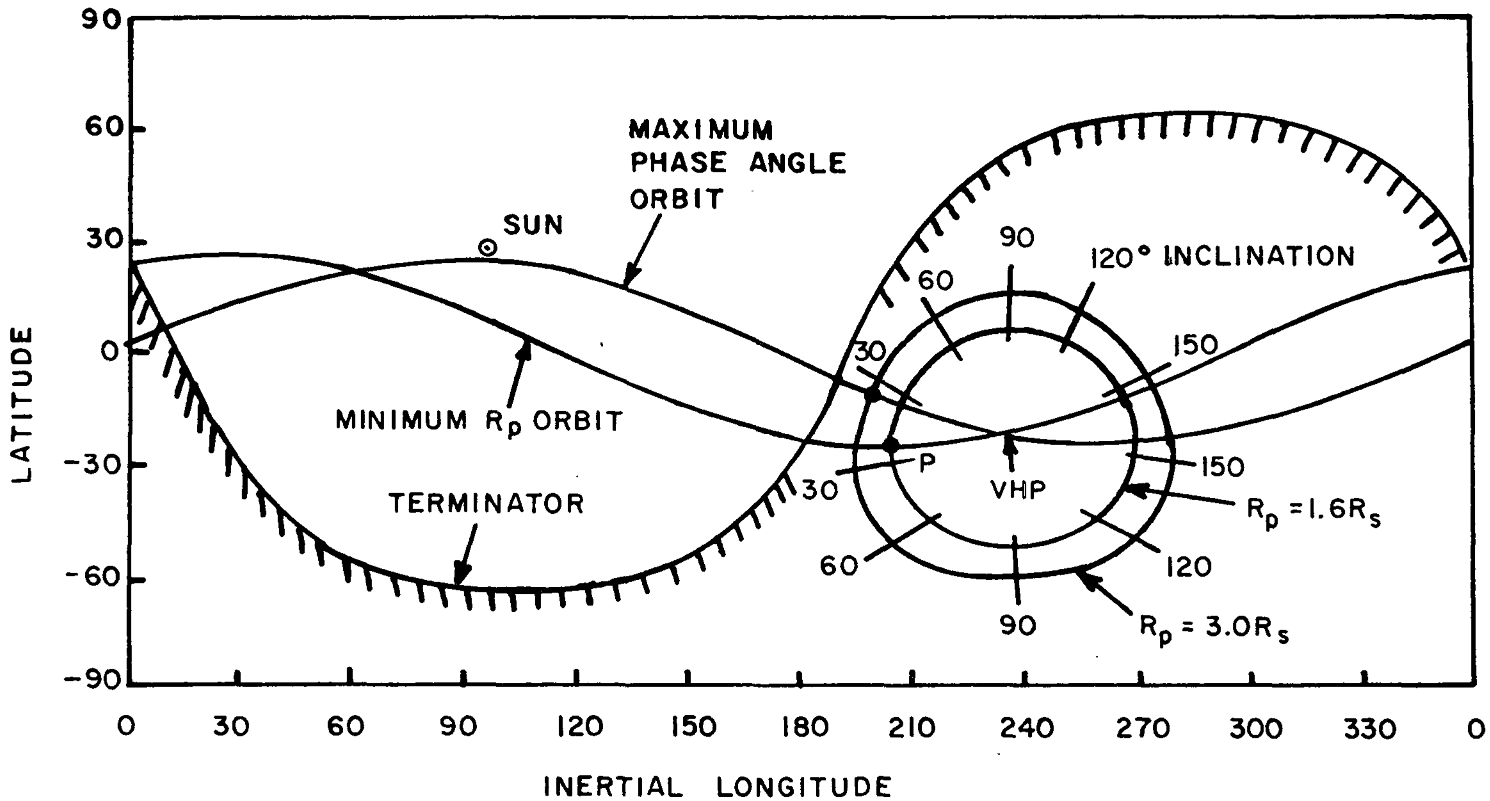


FIGURE 4-2 PERIAPSE LOCATIONS FOR A SATURN ORBITER

Saturn's satellites are in near circular orbits between 3.1 and 24.8 R_s and have very small inclinations. A close pass can be arranged for any one of them by selecting an inclined orbit for the spacecraft with a node near the satellite's semimajor axis. An orbit which passes near Titan, Saturn's largest satellite, will be discussed later. To obtain close up data on many satellites would require frequent changes in the orbit orientation — a rather costly process. It is far easier to establish an equatorial orbit by using a plane change at the apoapse of an intermediate orbit and then adjust the orbit period at periapse to get the desired satellite encounters. The magnitude of the velocity increment required for a plane change performed at the apoapse of a 3 x 100 R_s orbit is given in Figure 4-3 as a function of arrival velocity, VHP, and approach declination. Declinations of 20 to 30° are typical of arrivals between 1984 and 1992, so that a ΔV of between 300 and 600 m/sec will be required for the missions studied in this report.

Since there are three pairs of satellites with orbit resonances, it may be possible to use the methods outlined by Niehoff (1970) to generate close encounters with each pair of satellites on several consecutive orbits. For Minas and Tethys there should be two such opportunities each 1.65 years, while for Enceladus and Dione there are two chances each 2.92 years. In these two cases the orbit period should be an integer times the period of the second satellite. There is a weak commensurability between these four satellites such that the period 30.15 days is appropriate for both pairs. This is also close to twice Titan's period of 15.95 days. Hyperion's period is 4/3 times that of Titan. Therefore, a period of about 15 days is a good choice for equatorial orbits and could easily result in multiple close encounters with a majority of Saturn's satellites. The exact strategy, of course, depends on the arrival date, but the major ΔV expenditure would be for the plane change.

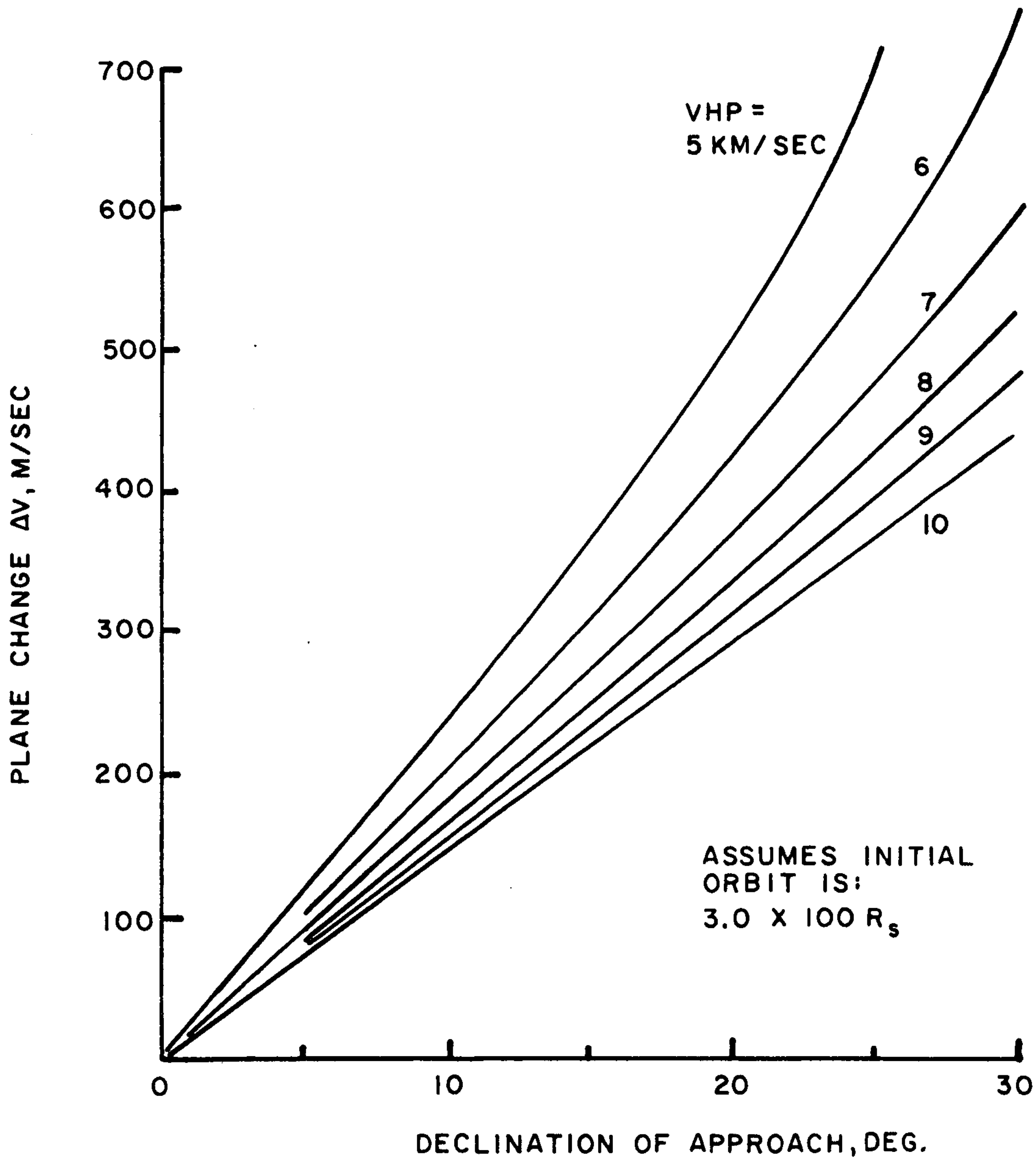
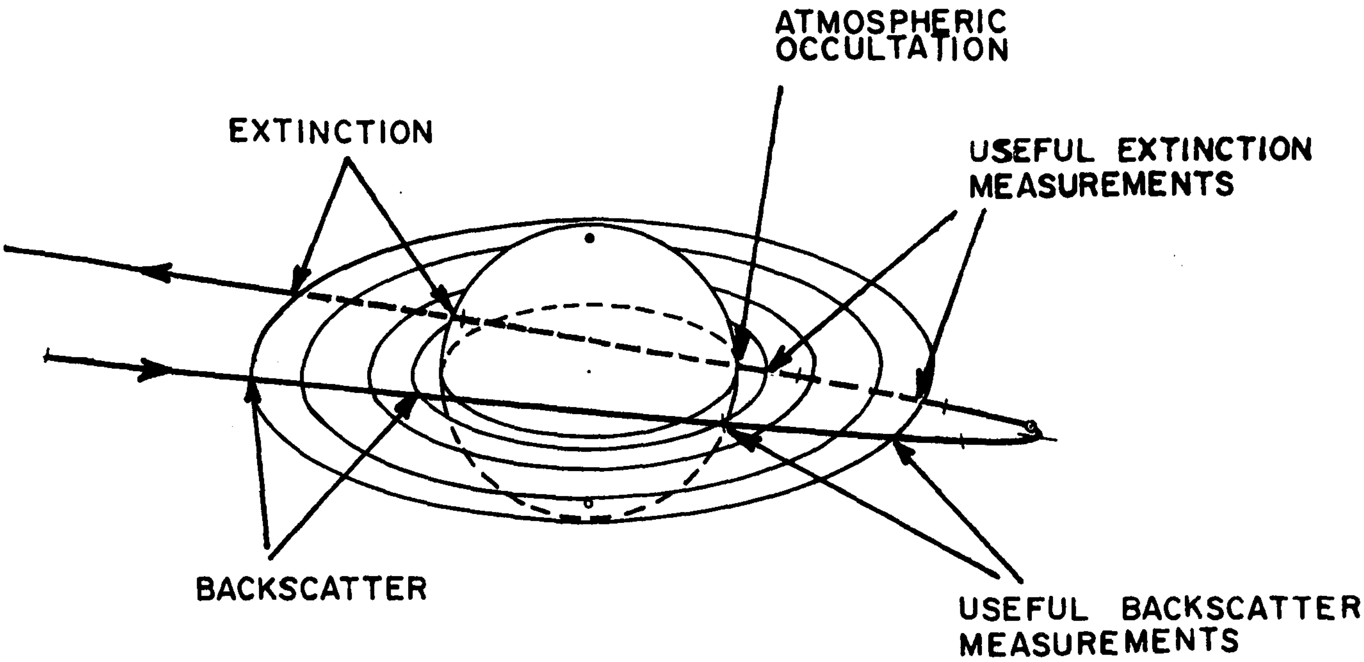


FIGURE 4-3 VELOCITY INCREMENT REQUIRED TO ACHIEVE AN EQUATORIAL ORBIT.

For study of the rings, it is desirable to have complete phase angle coverage from 0° to 180°. This means that the orbit should be designed to have 0° or backscatter point coverage over the entire radial extent of the rings and similar opportunities for 180° or extinction, preference being given to the latter. Drawing a picture of the orbit and the rings as seen from the sun is a good way to evaluate the phase angle coverage. When the spacecraft's path as seen from the sun passes in front of the rings, backscatter data can be acquired from the point in the rings which is directly behind the spacecraft. Similarly, as the spacecraft goes behind the rings, extinction measurements can be made at the point in the rings which is between the sun and the spacecraft. Since the earth and the sun are never more than 6° apart as seen from Saturn, the view from the earth, which determines the opportunities for radio occultations, is similar to the view from the sun.

Phase angle coverage is maximized by selecting the orbit plane which includes the subsolar direction. This is illustrated in Figure 4-4a for an orbit passing <u>near</u> the subsolar point, since one passing through it is a straight line when viewed from the sun. This is the maximum phase angle orbit shown in Figure 4-2. The spacecraft approaches Saturn from the left and two segments of 0° phase angle coverage are obtained over the full radial extent of the rings. Spacecraft periapse, taken as 3.0 R_s, is close to the node. Then the spacecraft passes behind the rings (twice) and the disc of Saturn as seen from the sun. Most other orbit orientation's don't have similar opportunities for both extinction <u>and</u> backscatter measurements. Often the disc of Saturn is also on the sun-spacecraft line, and thus interferes with ring measurements. Even trajectory paths near the subsolar point for 1977 and 1978 Jupiter-Saturn missions result in Saturn blocking the rings (Wells, unpublished).



(a) MAXIMUM PHASE ANGLE COVERAGE ORBIT

(b) MINIMUM PERIAPSE RADIUS ORBIT

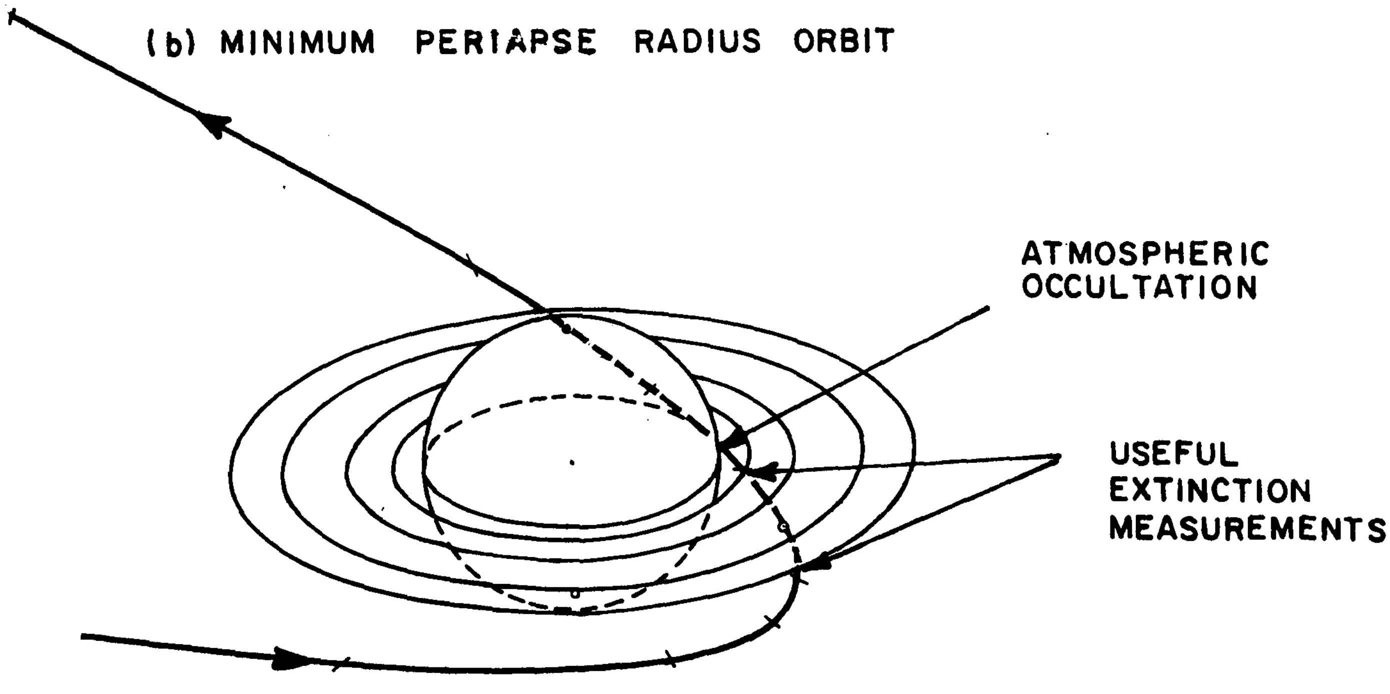


FIGURE 4-4 VIEWS OF ORBITS FROM THE SUN

A relatively small change in the orientation of this orbit will put the other node at 20.3 R_s. About 1.7 days after periapse the spacecraft will, if the timing is right, approach Titan with a relative velocity of 6.8 kn/sec and a phase angle of 75° so that over half of Titan's disc will be illuminated. It should be possible to have many encounters if the orbit period is a multiple of Titan's. Either the initial capture can be made into the orbit that encounters Titan or a plane change maneuver can be made at the apoapse of the maximum phase angle orbit.

If an orbit is to have a periapse of less than 3.0 R_s, then the ring hazard constraint limits the range of possible orbit orientations so that in general it will not be possible to get complete radial scans of the rings at phase angles of both 0° and 180°. This happens because the orbit described above has its periapse near a node whereas it is necessary to separate them to avoid the rings. If the argument of periapse is 90°, the periapse radius can be 1.6 R_s, the minimum. The plane of this orbit is ullustrated in Figure 4-2 and the phase angle coverage in Figure 4-4b. No backscatter data is obtained, but solar extinction and radio occultation data are acquired for all ring radii. The distance between the spacecraft and the ring location blocking the sun or radio signal is somewhat less than in the case discussed earlier. The smallest phase angle is around 15°, which is not much larger than the maximum for earth-based observers (6°). At periapse, the spacecraft is 0.7 R_s above the ring plane so that the resolution of the TV is about 2 km/line. However, the spacecraft can only view the unilluminated side of the rings at such close range.

Each of these two orbit types could be used to determine the composition of very small ring particles with an impact mass spectrometer. The radius at which the spacecraft crosses the ring plane should then be reduced from 3.0 R_s to the smallest safe distance. For the first orbit this must be done by reducing the periapse radius by a propulsive maneuver at apoapse. For 125 m/sec of ΔV the periapse of a 30-day orbit can be reduced from 3.0 to 2.3 R_s. Oblateness perturbations will reduce the nodal radius of the second orbit type if they are not compensated for by small apoapse impulses. This process is rather slow. About 10 orbits are needed to reach 2.3 R_s.

The ideal orbit for the study of the magnetosphere should cross the boundary with the solar wind and allow ample opportunity to study the radiation belts and the details of Saturn's magnetic field. The radiation belts are not expected for magnetic shell parameters, L, of less than 2.3 R_s, the outer radius of the observed rings. Measurements of the trapped particles near the inner edge are needed to understand the loss mechanisms. Taking an orbit with a periapse of 1.60 R_s for which the argument of periapse, ω, is 90° and a typical inclination of 30° to the magnetic equator gives a minimum L from Figure 4-5 of 1.35 times R_p or 2.15 R_s.

The general form of the planetary magnetic field can probably be determined from any orbit. However, the deviations from a dipole are most easily detected at close range. For example, the minimum periapse radius orbit discussed above is five times more sensitive to quadrupole terms than is an orbit with a periapse and a minimum L of 3.0 R_s.

Since little is known about the strength of Saturn's magnetic field, it is not known where the bow shock and magnetopause boundaries are. Haffner (1971) has suggested that the latter is at about 50 R_s in the subsolar direction and two or three times that perpendicular to the sun-Saturn line. Thus for prograde orbits, which have their periapse near the

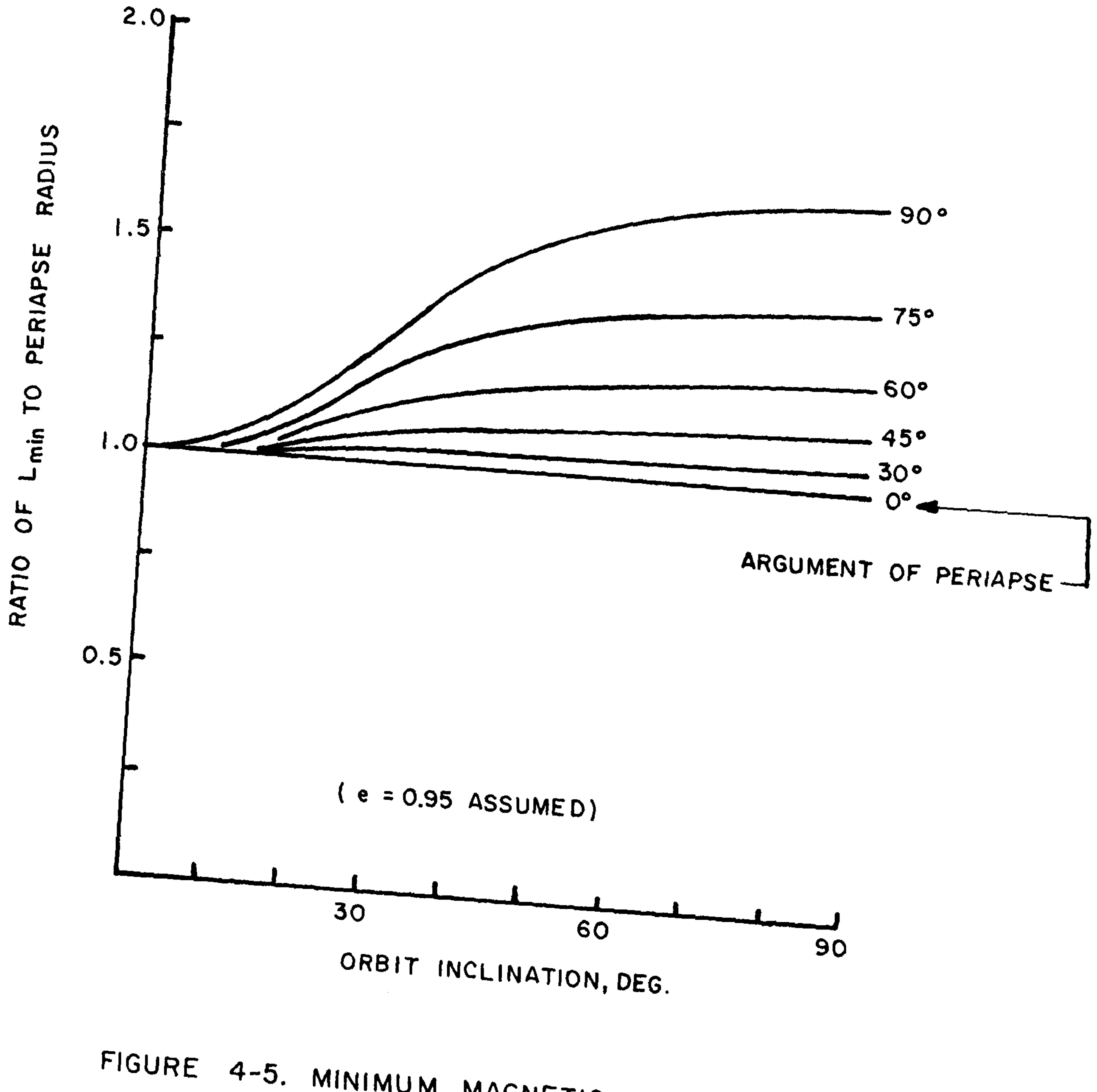


FIGURE 4-5. MINIMUM MAGNETIC SHELL PARAMETER (L_{min})

terminator, an apoapse of about 100 R_s or a period of more than 60 days is needed. But because of uncertainties in the location of the boundaries, and a frequent desire to have short period orbits for other more important observations, it would be unwise to select the orbit period to provide data on the solar wind interaction. The orbit orientation which would have the shortest period and also penetrate the boundary regions would have its apoapse near the subsolar direction. This can be achieved by using the same orbit plane as the maximum phase angle coverage orbit, but making the spacecraft motion retrograde. Other moderate inclination retrograde orbits could also be used.

Studies of the atmosphere of Saturn will be done with such techniques as imagery, spectroscopy, radiometry and occultations. As explained in Section 3, only TV's and spin scan imagers operating in the visual can be designed to operate at distances typical of orbit apoapse. All the others will have to collect their data near periapse. Clearly, short period orbits are to be favored since, as Figure 4-6 shows, they spend a larger fraction of their time near the planet. For orbits with the same period, however, the difference between a periapse of 1.6 R_s and one of 3.0 R_s is very small for altitudes greater than 3.0 R_s and there is very little time, amounting to 2 percent or less of the orbit period, during which the altitude is less than 3.0 R_s.

The fraction of the orbit period can also be interpreted in terms of the percentage of data obtained, assuming a constant acquisition rate. The altitude can also be converted to instrument resolution if the field of view is known. The TV described in Section 3 had an angular resolution of 45 μrad per TV line. From an altitude of 60 R_s, the apoapse of a 32^d orbit, this represents a surface resolution of about 300 km/line pair. About 10 percent of the TV pictures can have a resolution of

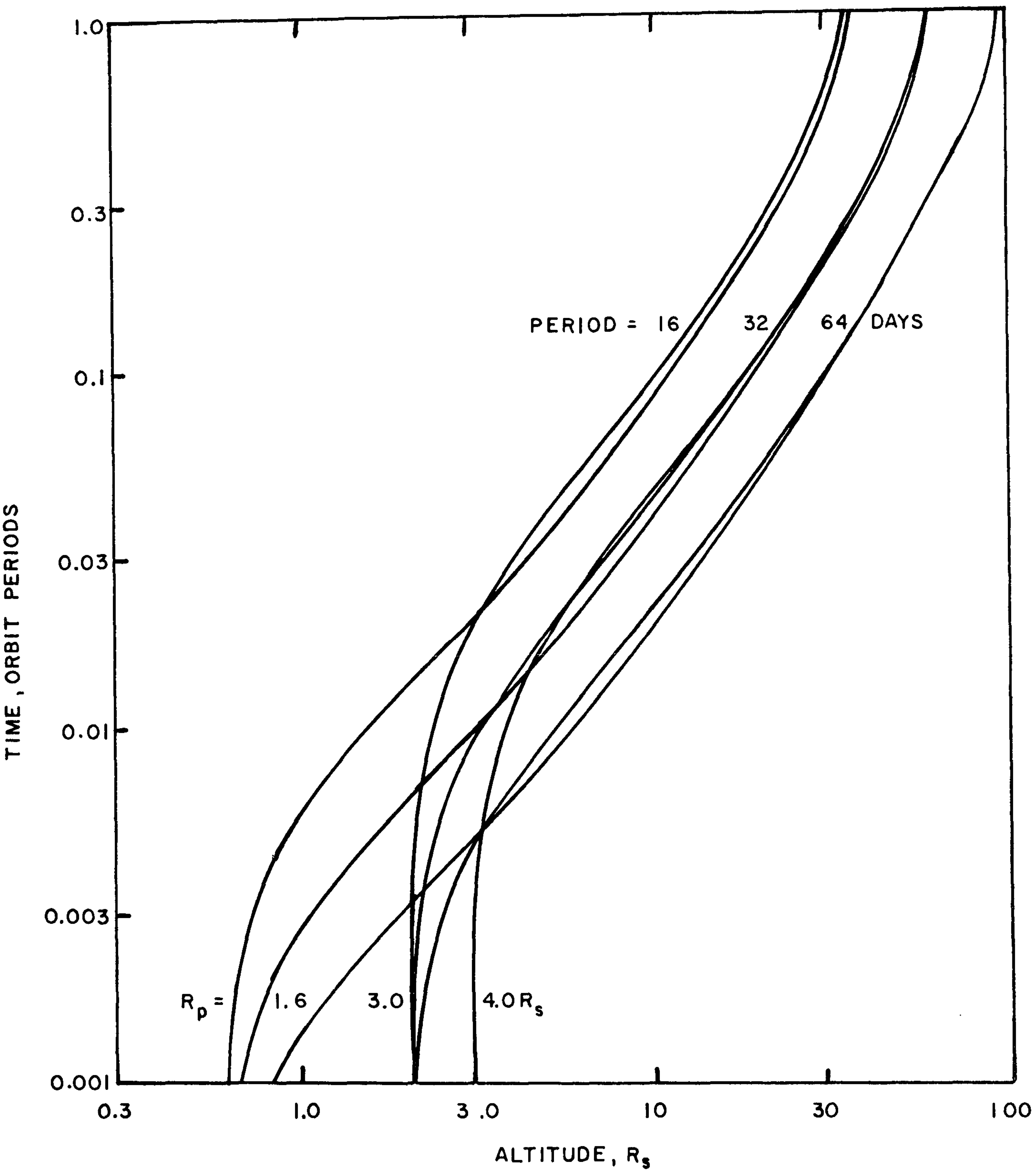


FIGURE 4-6 TIME VS. ALTITUDE (OR DATA VS. RESOLUTION)

at least 100 km/line pair which would be obtained during the 10 percent of the time the spacecraft altitude is less than 18 R_s. Only 2 percent of the pictures will have resolutions as good as 30 km although a tape recorder can be used to improve somewhat on the low percentage of high resolution TV frames.

The orientation of an orbit which would maximize the value of atmospheric measurements would provide adequate illumination of Saturn's disc at apoapse, and a wide range of phase angles near periapse. An opportunity for occultation and extinction measurements on the atmosphere should be included. For the two orbits shown in Figure 4-4, the entrance of the spacecraft into occultation, but not its exit, can be observed without interference from the rings. However, for many other orientations both opportunities will be obstructed because, as seen from the sun in February of 1989. the rings virtually surround the planet. Only for latitudes within about 15° of the equator does the atmospheric occultation occur without one of the rings also being occulted. This is typical of the conditions from 1985 through 1990. There follows a period of ever improving conditions, at first near the poles, until 1995 when rings will again be edge on and thus would not interfere with atmospheric occultation measurements at any latitude.

The orientation of the orbit also determines the viewing conditions at apoapse. Since the prime objective there is long term monitoring of global circulation patterns in the atmosphere, a well illuminated disc is very desirable. In general, prograde orbits of moderate inclination have apoapse views similar to those shown in Figure 4-7a for the orbit with maximum phase angle coverage. For an orbit period of 32 days the interval between these views is 9.5 days so that over 50 percent of the orbit is represented here. Half of the northern hemisphere which is

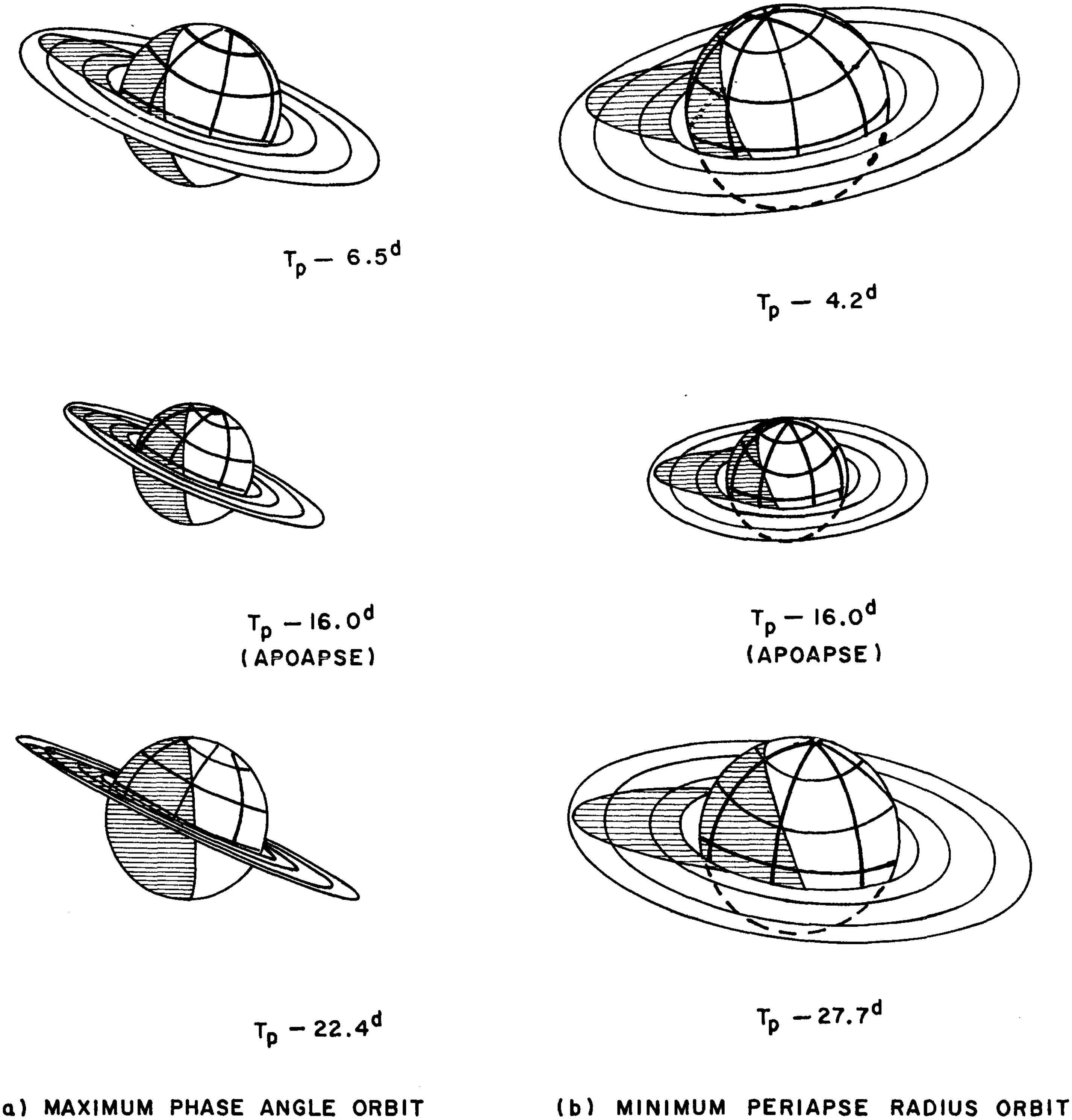
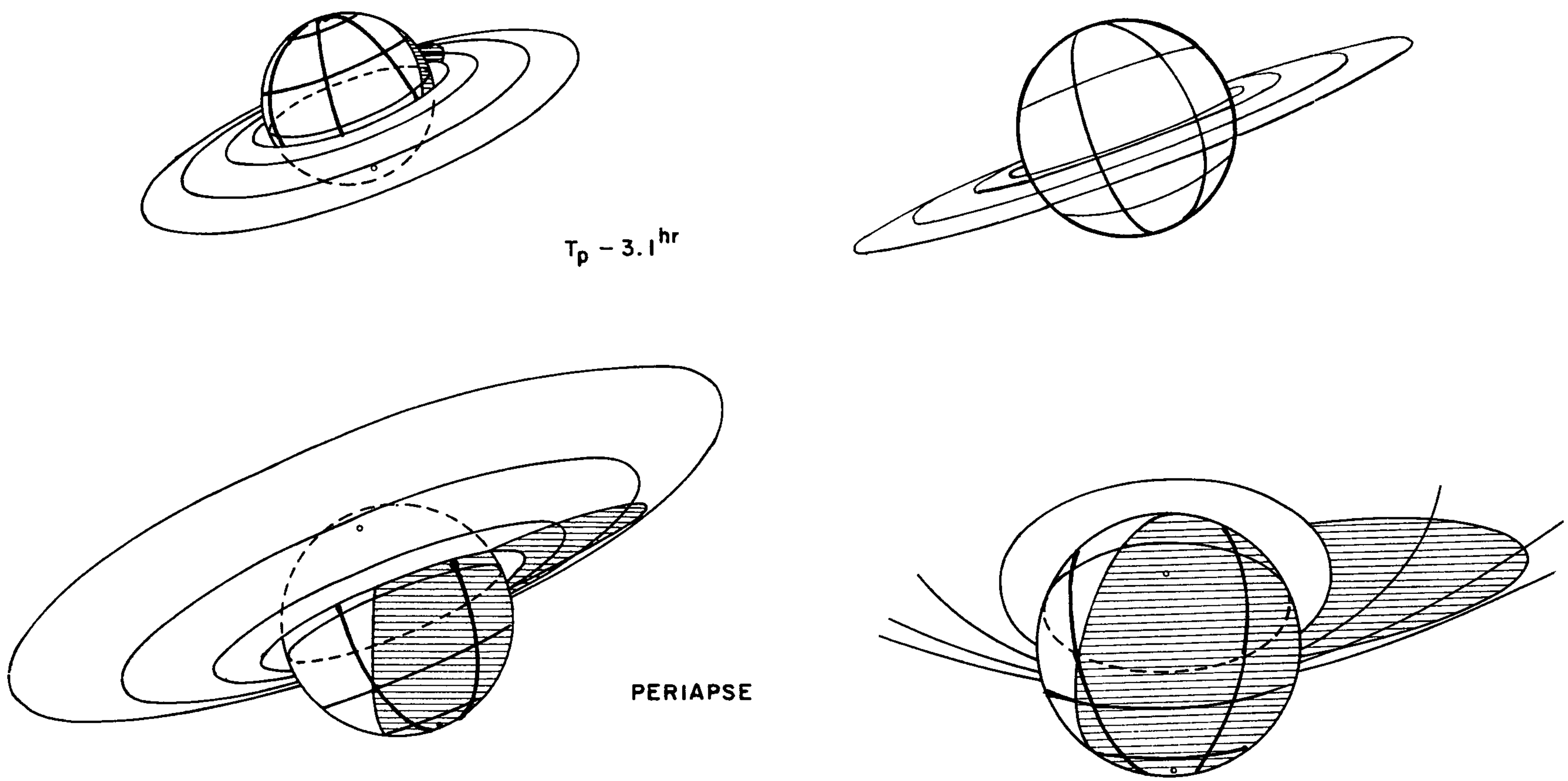


FIGURE 4-7. VIEWS OF SATURN NEAR ORBIT APOAPSE

illuminated by the sun can be seen so that each TV frame includes at least 25 percent longitudinal coverage. Views of the southern hemisphere which is illuminated indirectly through the rings can also be obtained when the spacecraft is near the equatorial plane. Thus, orbits with a nodal crossing near apoapse are preferred. Because the rings would never get in the way, the equatorial orbit that is needed for multiple satellite encounters would also be a good orbit for general observations of the atmospheric circulation. The one drawback is that the polar regions are always foreshortened. The minimum periapse radius orbit, as can be seen in Figure 4-7b, has a good apoapse view of Saturn's northern hemisphere. But because the spacecraft latitude is more than 20°N, the rings cover the southern hemisphere. This type of orbit would have a lower inclination, and a better view of the second hemisphere, if the arrival date were within a couple years of the rings being edge on,which they are in 1980 and 1995.

There are also important measurements, including spectroscopy at all wavelengths, which must be done when the spacecraft is near periapse. The node of the maximum phase angle coverage orbit is about 30° before periapse, so until that time the spacecraft is in an excellent position to study the directly illuminated (northern) hemisphere. But as Figure 4-8 shows, a half illuminated southern hemisphere is seen at periapse. A spacecraft in the minimum periapse radius orbit has similar coverage for altitudes of 3.0 R_s or more, but is below the ring plane whenever its attitude is less than 2.0 R_s; thus this orbit does not provide a better opportunity for measuring reflected solar radiation at lower altitudes. At periapse foreshortening, combined with the larger sun to periapse angle, results in a view which is mostly unilluminated.



(a) MAXIMUM PHASE ANGLE ORBIT

(b) MINIMUM PERIAPSE RADIUS ORBIT

FIGURE 4-8. VIEWS OF SATURN NEAR ORBIT PERIAPSE
(NOT TO SAME SCALE)

Although retrograde orbits are rarely given serious consideration, they would in general have a better view of Saturn from apoapse. For example, a retrograde moving space-craft in the maximum phase angle orbit plane would have its apoapse very near the Saturn-sun line and would then view a fully illuminated disc (similar to the view from the sun in Figure 4-4.) However, a retrograde orbit has disadvantages. The velocities relative to Saturn's atmosphere and satellites are higher. For measurements of the illuminated disc the altitude of the spacecraft is larger since the periapse is opposite the sun rather than near the morning terminator.

It has been shown in this section that the maximum phase angle orbit is very useful for studying the atmosphere, the rings and Titan. The minimum periapse radius orbit is best for magnetospheric measurements and the equatorial orbit for satellite observations. The basic tradeoff between the first two orbits is study of Titan rather than the interaction of the radiation belts with the rings. The full science payload which is inertially stabilized is well suited to both satellite and magnetospheric studies. But, if some instruments must be dropped, then the payload selections should reflect the capabilities of the orbit. Thus, the fields and particles experiments should remain on a spacecraft in the minimum periapse radius orbit and the spectrometers on the maximum phase angle coverage orbit. The equatorial orbit emphasizes multiple satellite encounters but has little to offer with respect to ring observations. This change in emphasis does not impact instrument preferences when compared with the maximum phase angle orbit. For the spin-stabilized science payload, the minimum periapse radius orbit is preferred and there would be no benefit from using an equatorial orbit. Since each of these three orbits has a unique capability, a program which uses several spacecraft in different orbits should be considered.

5. SPACECRAFT DEFINITION

In this section the requirements placed on spacecraft subsystems during a Saturn orbiter mission are considered relative to the capabilities of either currently available or proposed subsystems of spacecraft for outer planet missions. Two spacecraft will be defined. The first will be based on the Mariner Jupiter-Saturn 1977 spacecraft which is now being designed. The MJS-77 spacecraft uses many Mariner and Viking subsystems, but the configuration is the same as the TOPS spacecraft which was originally proposed for the longer JSP, JUN and JSUN missions. The Pioneer 10 spacecraft which has been built and launched to Jupiter is the model for the second case. The results of this section will be the required total spacecraft mass as a function of the hyperbolic approach velocity, one curve for each spacecraft/orbit combination. This will be compared in the following section with launch vehicle performance which can be expressed in the same format.

5.1 Mission Requirements

Two science payloads, one appropriate to each spacecraft, were selected in Section 3. The support requirements, weight, power, data rate and data storage, for these two payloads are given in Table 5-1. A typical flight time for Saturn missions is four years to which one year of operation (ten to twenty orbits) has been added to give a five year mission duration. The total velocity increment (ΔV) required for typical missions, includes an orbit capture impulse of 2.00 km/sec, 150 m/sec for orbit trim maneuvers when satellites are to be encountered and about 300 m/sec for the plane change needed to have an equatorial orbit. The requirements for midcourse corrections arise from launch vehicle injection errors, tracking and orbit determination inaccuracies and planetary quarantine restrictions.

Table 5-1

SPACECRAFT CHARACTERISTICS

SPACECRAFT CHARACTERISTIC	SATURN ORBITERS		CURRENT SPACECRAFT	
	MARINER	PIONEER	MJS-77	PIONEER 10
Science Payload, kg	60	40	70	30
Science Power, w	79	41	67	24
Data Acquisition Rate, kbps	132	12	115	2.0
Data Storage, 16^6 bits	560	0.3	560	0.05
Antenna Diameter, m	3.6	2.7	3.6	2.7
Transmitter Power, w	20	10	20	8
Data Transmission Rate[a], kbps	45	12	45	0.5[b]
Power Needed, w	370	160	375	108
Power Available EOM, w	365	240	375	108
Mission Duration, yrs	5	5	4	3
Dry Weight, kg	788	440	680	230
Propulsion Isp, sec	375	375	225	225
ΔV, km/sec	2.30[c]	2.15[c]	0.14	0.20
Total Weight, kg	1500	800	725	257

a - at 9.5 AU to 64 m DSIF antenna, X-band
b - S-band only
c - 30 day orbit with 3.0 R_s periapse

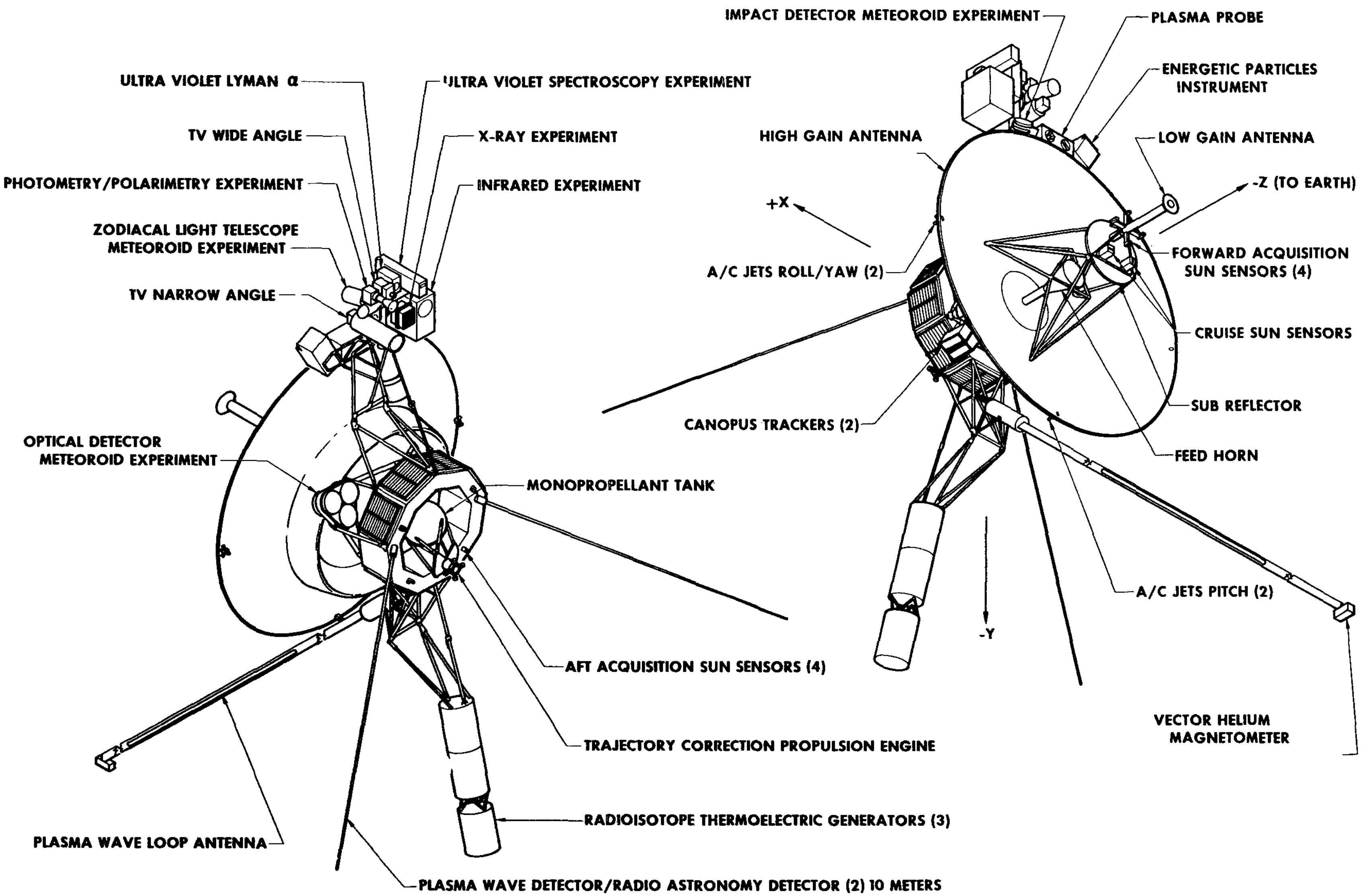


FIGURE 5-1 MARINER SPACECRAFT FOR JUPITER-SATURN '77

For a Saturn orbiter the resulting ΔV allowance was assumed to be similar to that for the MJS-77 and Pioneer missions. The satellite encounter provision will be used for period adjustments to put the spacecraft into phase with the satellites and to keep it there despite perturbations during close encounters (Niehoff 1970). The other spacecraft characteristics listed in Table 5-1 are explained in the separate discussions of the Mariner and Pioneer spacecraft that follow. A weight estimate and the technology status of each subsystem are given in Table 5-2.

5.2 A Mariner Saturn Orbiter

A basic characteristic of a Mariner spacecraft is its 3-axis stabilization and science platform with two degrees of freedom (see Figure 5-1). The instruments mounted on the remote scan platform will have an unobstructed view of about three-fourths of the celestial sphere. The location of the blind spot is determined by the relative location of the scan platform and the Canopus sensor and can be optimized for the selected orbit. By executing a roll, the instruments can view all of space. Note that the Mariner Mars spacecraft upon which JPL (1971) based their Jupiter orbiter does not have a remote science platform.

The telecommunication subsystem of the MJS-77 spacecraft is currently expected to be able to receive commands at a 4 bps rate at well beyond Saturn's range, to transmit data at a nominal 45 kbps rate back to the earth and to participate as a science experiment (see Section 3.1). The downlink data performance is based on 20 watts of transmitted power at X-band frequencies from the spacecraft's 3.6 m parabolic antenna. The radio signal is received at a 64 m antenna of the Deep Space Information Facility with an elevation angle of 25° or more. When the error rate is 0.5 percent, the nominal data rate is 45 kbps (NASA/OSS 1972a). Lower error rates for non-imagery data are

TABLE 5-2

SPACECRAFT SUBSYSTEMS: WEIGHT AND STATUS

SPACECRAFT SUBSYSTEM	MARINER SATURN ORBITER		PIONEER SATURN ORBITER	
	WEIGHT (kg)	TECHNOLOGY STATUS[a]	WEIGHT (kg)	TECHNOLOGY STATUS[b]
SCIENCE	60	modified	40	modified
SCAN PLATFORM	30	similar	--	-----
TELECOMMUNICATIONS	55	modified	23	new
DATA STORAGE	14	similar	5	new
ATTITUDE CONTROL	50	similar	20	similar
COMMAND/CONTROL	19	similar	4	similar
POWER	150	similar	102	new
THERMAL	13	similar	8	similar
CABLING	35	similar	13	similar
STRUCTURE, MISC.	160	modified	76	modified
ANTENNA	22	similar	25	similar
PROPULSION[c]	180	new	124	new
DRY WEIGHT	788		440	
PROPELLANT	712		360	
TOTAL	1500		800	

a Relative to MJS-77

b Relative to Pioneer 10

c Includes propellant proportional inert weight of 114 kg and 58 kg respectively desirable and 5×10^{-5} can be easily obtained if this data is transmitted at half the rate of the imagery. While it is not possible to have real time imagery at 130 kbps, TV data at a reduced format of 416 x 350 can be transmitted directly. The weight of this system is 15 kg less than for MJS-77. The reduction is obtained from a new radio receiver design proposed for MJS-77 and substituting solid state S-band amplifiers for the current TWTA's. The new receiver could provide for thermal noise measurements and antenna pointing corrections via error channels connected to monopulse feeds. The latter is especially important during atmospheric occultations when the radio signal is strongly attenuated and is also refracted up to 15° from the nominal direction. A data rate of about 120 kbps can be obtained with forty watts of transmitter power and a 4.2 m antenna as was proposed for TOPS Grand Tour spacecraft. The main impact of these changes would be an increase of about 60 w in the power requirements.

The data storage system is based on the Viking tape recorder which has a capacity of 5.6×10^{8} bits or about 100 TV frames. This is equivalent to one hour of continuous imagery but in practice only near periapse or during a satellite encounter will a hundred frames be desired in an hour. The record rate is 130 kbps and there must be several playback rates keyed to data transmission rates with a 5 kbps allowance for real time science. Readout time is four hours at the maximum rate of 40 kbps. The command/control subsystem is also a Viking component. It provides pre-programmed timing and sequencing functions for the spacecraft. Up-dates, especially for trajectory and orbit correction maneuvers, can be performed during the mission through the command receivers. Part of this subsystem's digital storage can be used as a buffer for science data.

The attitude control system for MJS-77 will include reaction wheels in addition to the cold gas thrusters used on previous Mariners. The celestial references are the sun and Canopus with rate integrating gyros providing the inertial reference during spacecraft maneuvers and occultations. The basic limit cycle is 0.8 mr with a 10.5 mr deadband for non-critical mission phases, primarily prior to orbit capture. The nominal attitude rate is ten microradiams per second but it may be several times this immediately following scan platform motion. While design changes from MJS-77 may be required by the larger weight and moments of inertia of a Saturn orbiter, the subsystem weight should remain the same.

Power for the spacecraft will be provided by three radioisotope thermoelectric generators. Based on current technology their combined output would be 410 w at launch and would drop to 365 w after five years. This is five watts less than the maximum demand estimated by adjusting the MJS-77 load (375 w) for the selected science instruments and radio subsystem redesign. It should not be too difficult to either save some power through redesigns of other subsystems or gain it with improved RTG technology. Another RTG unit should be added when considering a higher power transmitter or all the science instruments, however. This is the reason why these options were not selected for the nominal Mariner spacecraft.

For the thermal, cabling and antenna subsystems there are no significant differences between MJS-77 and a Saturn orbiter. The antenna weight, however, was estimated using a scaling relationship (Klopp and Wells 1971) rather than the 6 kg quoted for MJS-77 (NASA/OSS 1972a). Some changes in the basic structural design will be required to accommodate the orbit capture propulsion system. Their effect on the structural weight has been estimated by comparing Mariner 6 and 7 to Mariner 9 and by comparing Mariner 9 to MJS-77.

It has been assumed that a space-storable FLOX/MMH retro propulsion system will be developed for use in the 1980's. This propellant has a specific impulse of 375. The nominal system has a 600 lbf thrust engine and has an inert weight of 66 kg plus 0.16 times the required propellant mass. (The characteristics of this system were supplied by D. L. Young of JPL which has long supported its development.) Other propellants such as F_2/N_2H_4 and OF_2/B_2H_6 have about the same performance. These space-storable combinations are significantly better than the earth-storable N_2O_4/MMH system used for Mariner 9 and Viking and which has an Isp of 285. The weights listed in the tables assume an orbit capture ΔV of 2.0 km/sec plus 300 m/sec for corrections to the interplanetary trajectory and to the orbit about Saturn.

The actual velocity increment required for orbit capture is a simple function of both the orbit dimensions and the hyperbolic approach velocity, VHP. Table 5-3 gives the ΔV needed as a function of orbit periapse radius and period assuming a VHP of 8.0 km/sec which corresponds to a flight time of four years.

Table 5-3

ORBIT CAPTURE REQUIREMENTS, km/sec

Periapse Radius, R_s	Orbit Period, Days		
	15	30	60
1.6	1.70	1.48	1.35
2.3	2.03	1.77	1.61
3.0	2.31	2.01	1.82
4.0	2.66	2.30	2.08

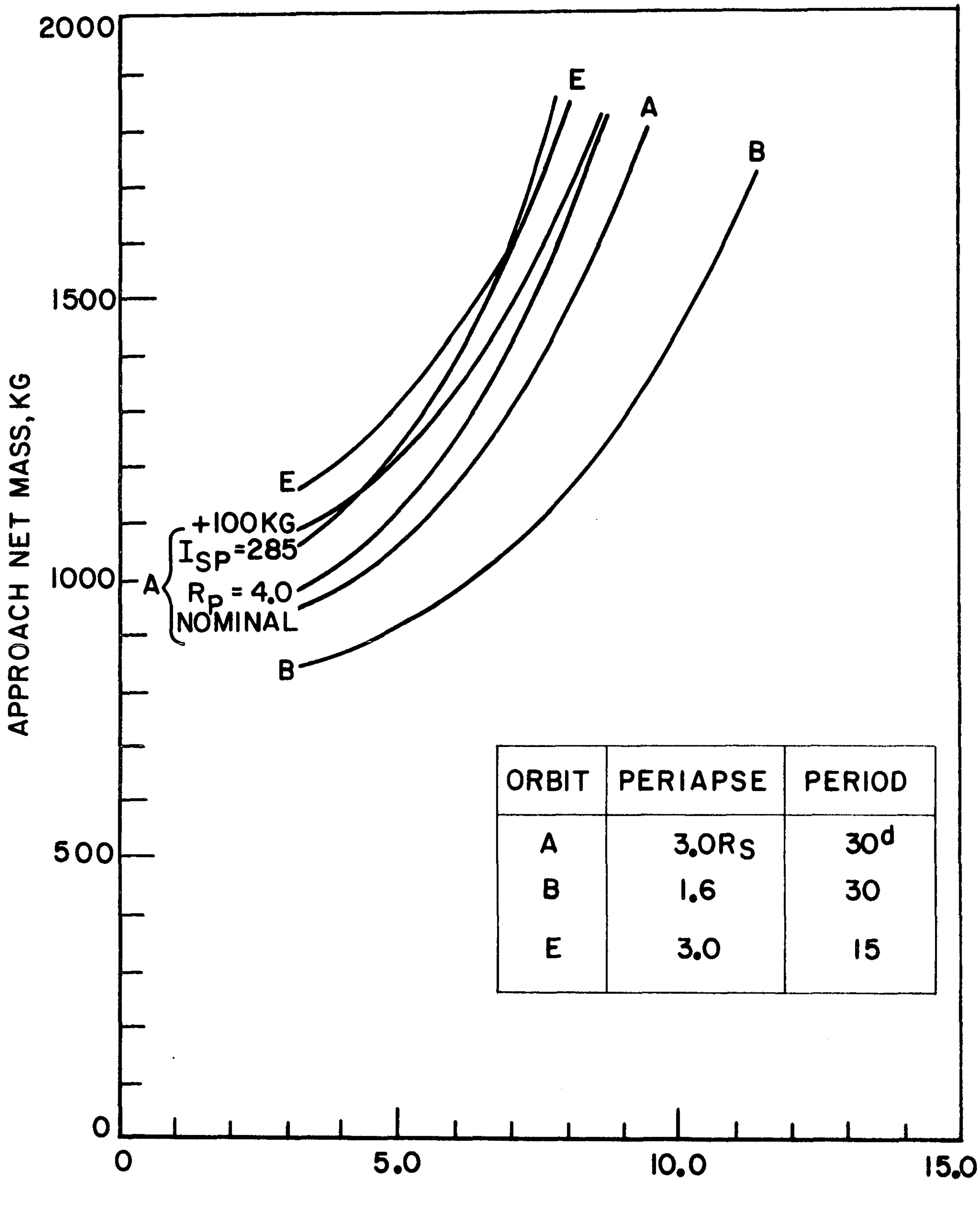


Figure 5-2 TOTAL WEIGHT OF MARINER SPACECRAFT

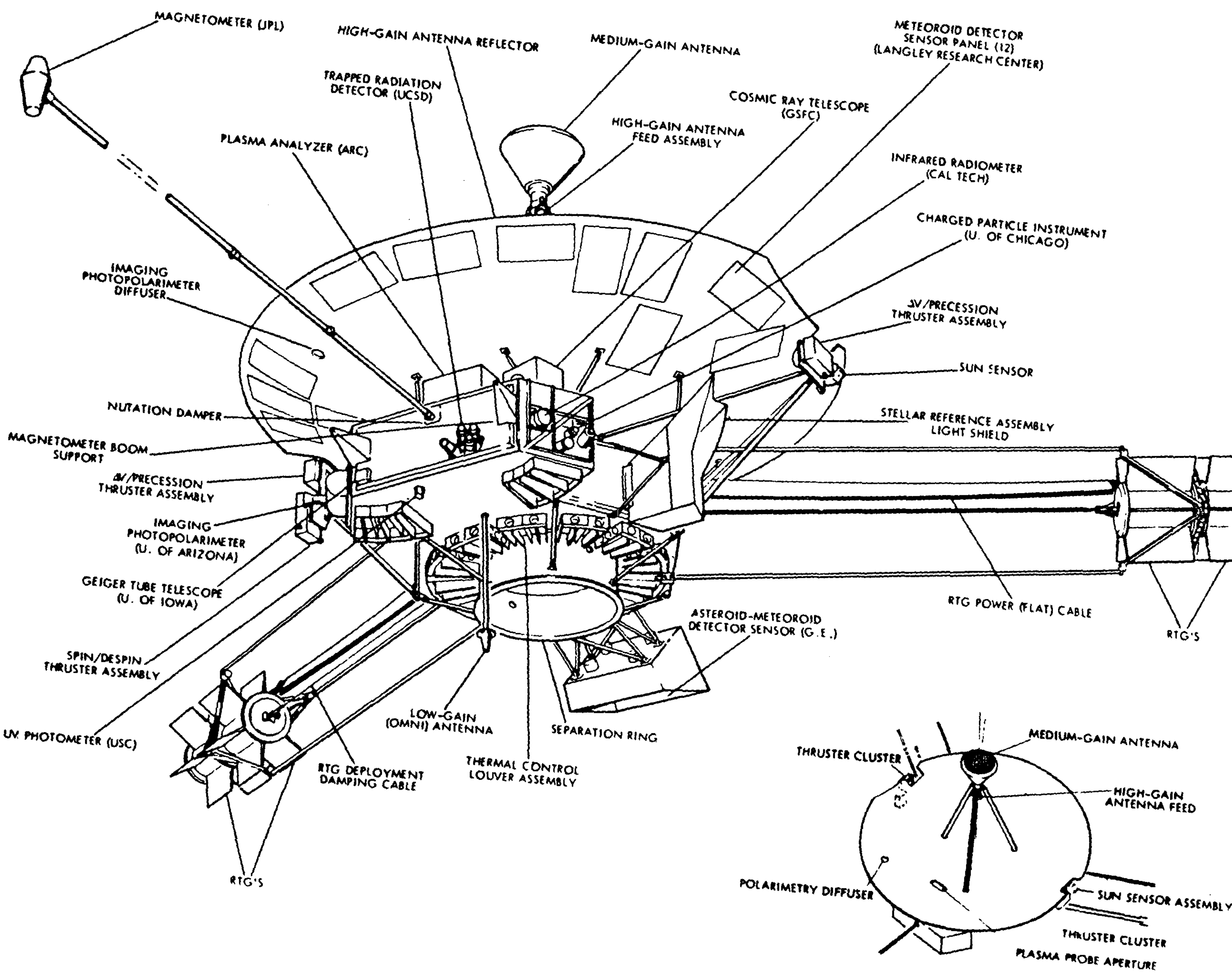
The total spacecraft mass is given in Figure 5-2 as a function of VHP for the three nominal orbits: A) The maximum phase angle orbit; B) The minimum periapse orbit and; E) The equatorial orbit for satellite studies. The ΔV provisions for maneuvers after orbit capture are 150, 0 and 450 m/sec respectively.

Since option B has the smallest ΔV requirement, it represents the minimum weight for a Mariner spacecraft for a Saturn orbital mission. Also shown are three variations of option A. One has a periapse radius of 4.0 R_S, for the next earth-storable propulsion was used and for the last the spacecraft mass was increased by 100 kg by adding more science and another RTG. In all three cases the mass requirement is less than for the equatorial orbit which is the most difficult mission. Thus, a launch vehicle which can do the equatorial mission can also accommodate any of these three changes in mission A.

5.3 A Pioneer Saturn Orbiter

Table 5-2 shows that changes are proposed for many of the Pioneer spacecraft subsystems. Most of them would be desirable for a Jupiter orbiter, too (NASA/Ames 1971). The basic concept of spin-stabilization with the spin axis pointed at the earth is retained as is the 5 rpm spin rate. Figure 5-3 shows the configuration of Pioneer 10. The science instruments selected for the Saturn orbiter (payload #2 from Table 3-3) are heavier than those on Pioneer 10, consume more power and have a higher data rate. There is no scan platform and so the instruments must include provision (set at 4 kg here) for pointing control in a plane which includes the spin axis. A complete scan of the celestial sphere can be made if the instrument is mounted beyond the edge of the antenna and if it can point at angles of 0 to 180° from the spin axis.

FIGURE 5-3 **PIONEER F/G SPACECRAFT**



The current Pioneer S-band radio transmitter is not effective at Saturn so the addition of an X-band link is desirable. The frequency change, block coding (like Mariner) and the 0.5 percent error rate give a factor of 24 improvement in the data rate. Dual band communications also greatly improve the accuracy of the radio tracking and occultation data. The 2.7 m spacecraft antenna diameter has been retained, but the weight of the Pioneer 10 radio system was increased by 8 kg to provide not only the X-band TWTA's but also additional receivers for the detection of antenna pointing errors.

A larger data storage unit is needed to buffer the data from the multi-element line scanner and a 0.3 million bit unit weighing 5 kg has been selected (NASA/Ames 1971). No change in the Pioneer command distribution unit is assumed although some increase in the number of commands that can be stored may be desired due to the increased delays (about 80 min.) in the receipt of radio signals.

The attitude control system of a spin-stabilized spacecraft is used to maintain the proper spin rate and spin axis. The Pioneer 10 spacecraft has two sets of attitude control thrusters located at the edge of the high gain radio antenna and control electronics to determine when to use the thrusters. Roll reference is provided by a star sensor. When a propulsion maneuver is needed, the spin axis is precessed to the desired location and checked by studying the outputs of the stellar and solar sensors. This process is reversed following the timed thrust of the propulsion system. When returning to the earth-pointing mode, the error sensing radio receivers can be used to "home" in on the uplink radio signal. Because the precession maneuvers are open-loop, it will be desirable to check them before initiating the ΔV or earth acquisition functions. Thus a ΔV maneuver at Saturn will take at least five hours or four

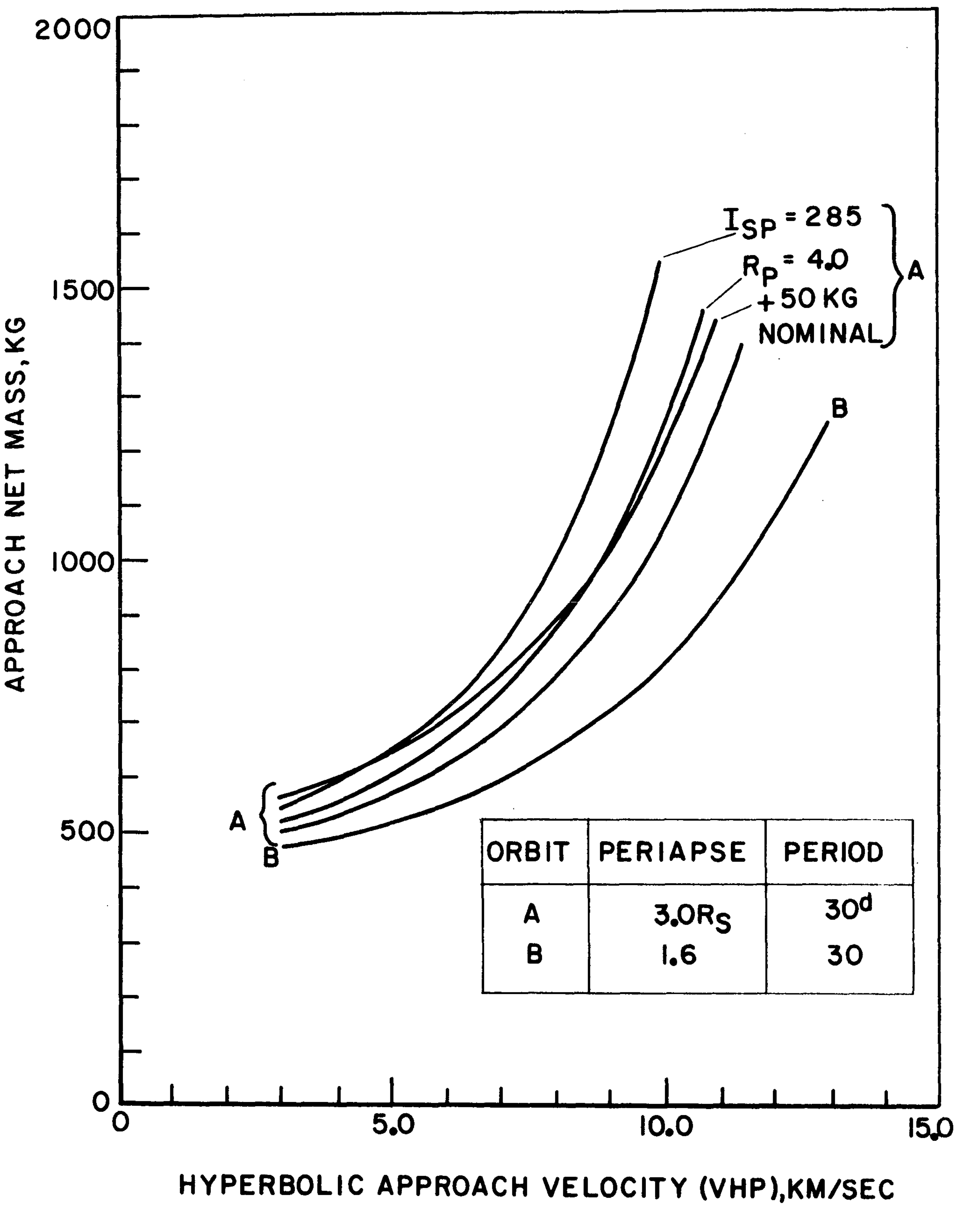


Figure 5-4 TOTAL WEIGHT OF PIONEER SPACECRAFT

times the radio signal propogation time. The performance of the radio receivers and transmitters appears adequate for 4 bps rates over the omni antenna for any spin axis.

The Pioneer power supply consists of four SNAP-19 RTG's which after five years are expected to provide only 90 w of power. However due to changes in the science package, the propulsion system and the radio transmitter, the proposed orbiter is expected to need about 50 w more than the current spacecraft. The best solution was to use two of the more advanced MHW units (the Mariner has three) rather than increasing the number of SNAP-19's.

There are the obvious structural changes needed for attaching the large propulsion system to the existing spacecraft. In addition somewhat stronger supports will be required for the larger RTG's. A new compartment for science instruments is also provided so that they may have a full 180° field of view. Together these alterations increased the structural weight by 50 percent. No change in the weight of either the thermal control or power distribution systems is anticipated.

The same propulsion system has been used for both the Pioneer and Mariner orbiters. In Table 5-2 the propellant weight is shown for a total ΔV of 2.15 km/sec. Since none of the Pioneer missions involve satellite encounters, the velocity allowance for midcourse and orbit trim maneuvers is set at 150 m/sec. Figure 5-4 shows the total spacecraft mass as a function of approach speed. As before the nominal B orbit is less demanding than the nominal A orbit mission. All three variations on the A orbit increase the approach mass requirement but are still below that for the Mariner cases.

All that remains is to estimate the performance of selected launch vehicles for some Saturn opportunities in the 1980's and to compare this to the spacecraft requirements.

6. INTERPLANETARY TRANSFERS TO SATURN

Two types of interplanetary trajectories were examined for Saturn orbiter missions: direct ballistic transfers, and solar electric low thrust transfers. Jupiter swingby trajectories to Saturn were examined since the advantages of the gravity assist diminish after 1978 and do not appear until 1996.

Earth-Saturn ballistic opportunities in the early 1980's occur every year except 1984. For this study, the 1980, 1982 and 1985 opportunities were used for payload calculations. Type I ballistic trajectory and payload data were obtained from four sources: Planetary Missions Handbook (IITRI/Astro Sciences 1972), Planetary Flight Handbook (NASA/OART 1969), the JPL SPARC program (Roth et al. 1968) and Launch Vehicle Estimating Factors (NASA/OSS 1972b). The first source shows that through 1985 there is steady improvement in the payload delivered into orbit about Saturn. The data of Rejzer (1967) indicate that launch requirements are steady between 1985 and about 1988 and do not return to this optimum level until 2000.

Solar electric trajectories to Saturn in the early 1980's are less sensitive to launch opportunity than are ballistic trajectories. Payload performance for SEP is virtually constant from 1980 to 1985, with only a slight variation in flight time for a given payload from one opportunity to the next. Thus, SEP payload data are shown only for the 1980 launch opportunity (1985 data are in Figure S-2). SEP performance data were taken from the Planetary Missions Handbook and the CHEBYTOP code (Hahn and Johnson 1971).

Table 6-1 presents launch vehicles and propulsion system parameters used for generation of payload data. The Centaur, as a stand-alone upper stage, does not have sufficient payload capability with either the Titan or Shuttle vehicles. Thus,

Table 6-1

FIXED PARAMETERS FOR SATURN ORBITER MISSIONS

LAUNCH VEHICLES: TITAN IIIE/CENTAUR/TE364-4
TITAN IIIE/CENTAUR/BII
TITAN IIIE/CENTAUR/SEP
SHUTTLE/CENTAUR/HE BII
SHUTTLE/CENTAUR/SEP

LAUNCH CONSTRAINTS: 20 day window
DLA < 40° for Titan vehicles

SOLAR ELECTRIC PROPULSION PARAMETERS:

POWER LEVELS:	15 kw, 20 kw, 25 kw
THRUST TIME:	400 days
SEP STAGE MASS:	300 kg + 30 kg/kw (jettisoned)
SPECIFIC IMPULSE:	3000 sec

ORBITS:

	Periapse	Period
A	3.0 R_s	30^d
B	1.6 R_s	30^d
E	3.0 R_s	15^d

for all ballistic missions a Burner II family solid propellant is employed. The Titan IIIE/Centaur/BII vehicle will probably be used for the MJS-77 mission. It is not known at this time what upper stages will be available for use with the Space Shuttle. The Centaur is somewhat smaller than the proposed expendable Tugs but much larger than the Agena or Transtage which have been suggested as interim upper stages. Thus, the Centaur comes close to stating the maximum Shuttle performance and is at the same time a well-known vehicle. The launch conditions are typical of current requirements for planetary missions. The SEP system parameters including the power range, are typical of those being used in current SEP stage design studies. The thruster specific impulse of 3000 sec for SEP is somewhat higher than optimum for outer planet missions, but is the technologically preferred value at the present time. The SEP stage mass is 300 kg plus 30 kg/kw of power at 1.0 AU and is jettisoned prior to orbit insertion. The SEP stage was provided with 400 watts of housekeeping power during the 400 day thrusting period. It was assumed that a space-storable propulsion system would be available for retro propulsion in the mission time-frame.

Figures 6-1, 6-2, and 6-3 present payload capability for ballistic launch systems in 1980, 1982 and 1985 respectively. Net approach mass at Saturn is plotted as a function of approach velocity. The flight time to Saturn is also shown.

Considering the spacecraft and orbits discussed in Section 5, the Shuttle/Centaur/HE BII has nominal capability to deliver only the Pioneer-class spacecraft into the A and B orbits in 1980. The points indicating this are labeled P-A and P-B. Performance increases slightly in 1982 in that the flight times are slightly shorter than those in 1980, and the Titan IIIE/Centaur/TE364-4 can place the Pioneer spacecraft into the B orbit.

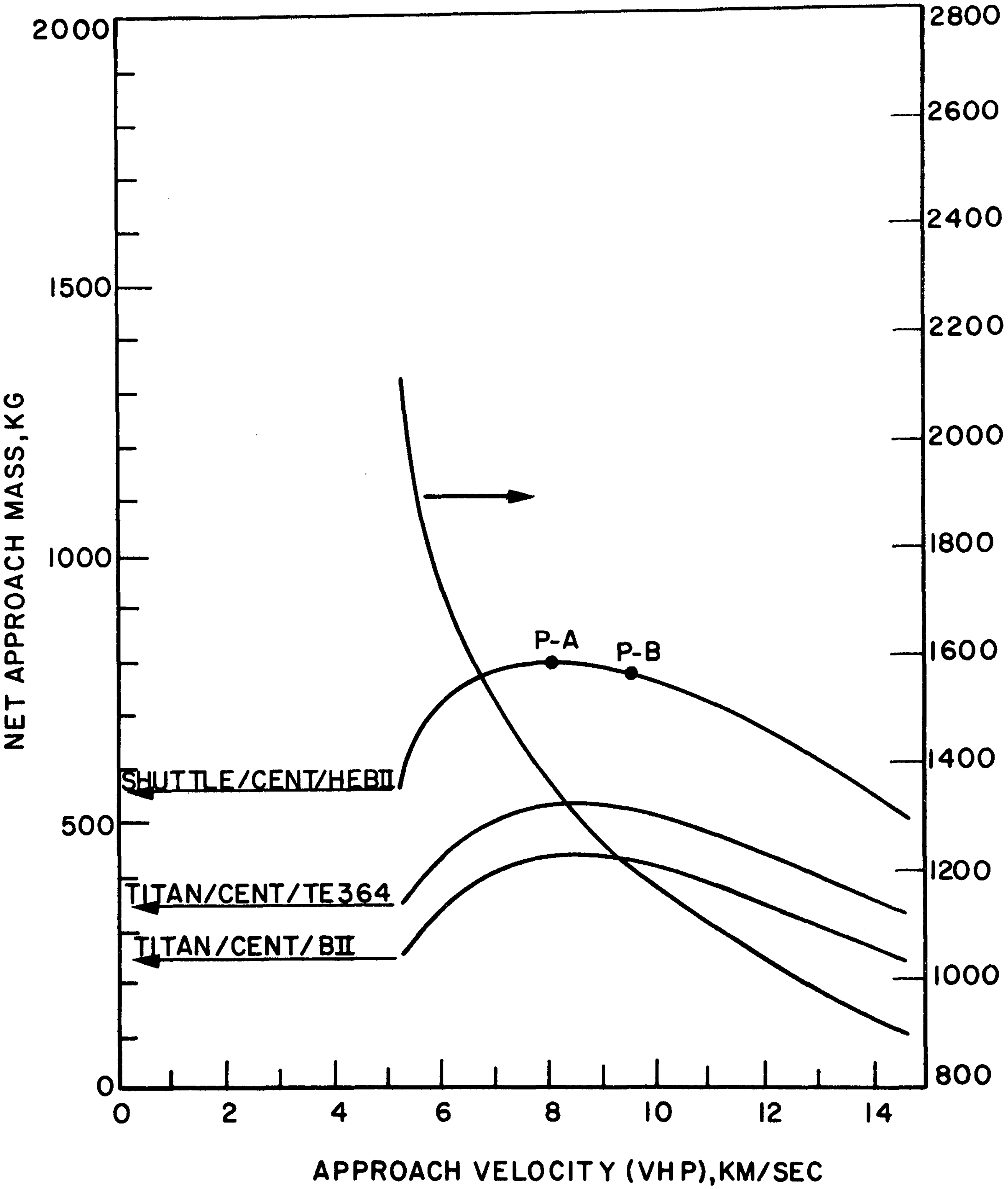


Figure 6-1 INJECTED MASS FOR 1980 OPPORTUNITY TO SATURN

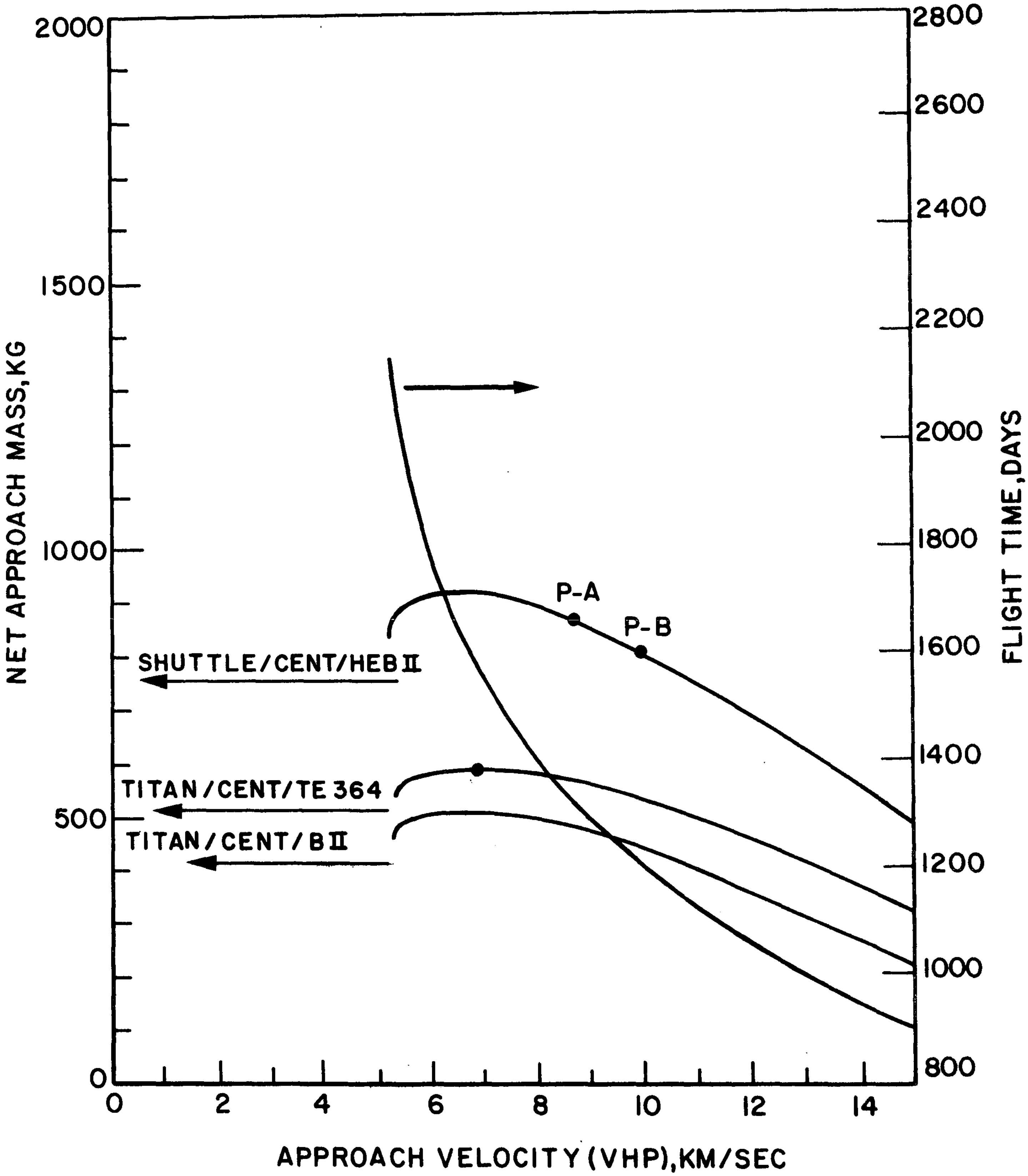


Figure 6-2 INJECTED MASS FOR 1982 OPPORTUNITY TO SATURN

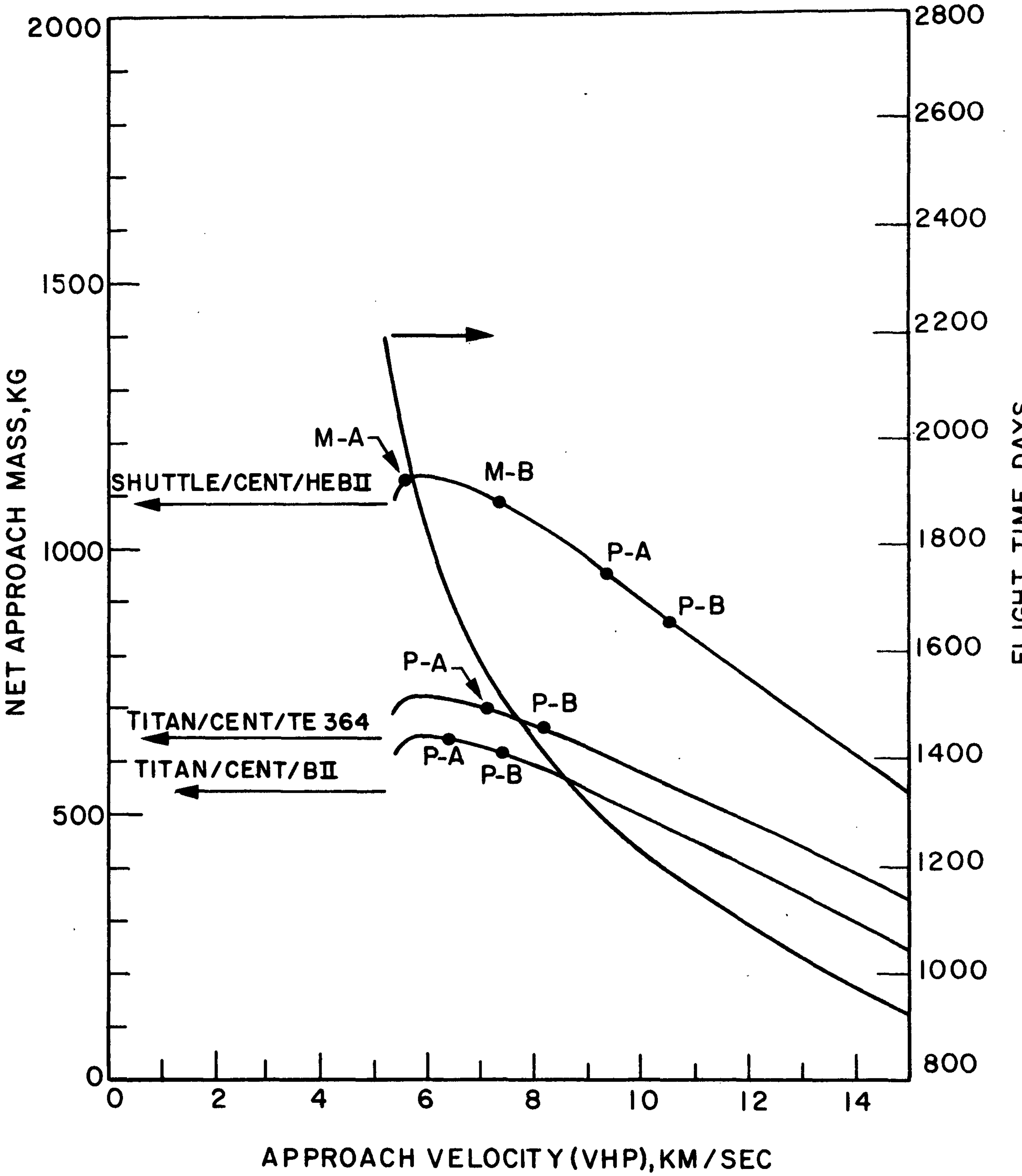


Figure 6-3 INJECTED MASS FOR 1985 OPPORTUNITY TO SATURN

The 1985 opportunity, however, represents maximum ballistic performance. Both Titan launch systems are able to place the Pioneer-class spacecraft into both the A and B orbits, and the Shuttle has gained the capability to deliver the Mariner-class spacecraft to both orbits.

In general, flight times longer than four years are not desirable because of spacecraft lifetime and performance margin considerations. Without an adequate performance margin there is little opportunity to adapt to changes in the spacecraft mass requirement or anticipated launch vehicle capabilities. This can be seen in the case of the 1982 data, where the Titan IIIE/Centaur/TE364-4 can place a Pioneer spacecraft into the minimum periapse orbit after a 4.3 year flight. The same launch vehicle cannot place this spacecraft into the slightly more difficult maximum phase angle orbit. A similar problem exists in 1985 for the Mariner spacecraft missions with orbit A taking 4.2 years and orbit B almost a full year longer. Note that for flight times of less than about three years the retro propulsion system becomes large compared to the spacecraft.

Solar electric propulsion provides the best overall performance, as seen in Figure 6-4. Payload curves are shown for three SEP power levels for both launch vehicles. The Titan/Centaur with SEP can deliver the Mariner-class spacecraft to the A and B orbits, except at the 15 kw power level, whereas the Shuttle/Centaur/SEP can also place the Mariner spacecraft into orbit E.

The tradeoff between SEP power levels is seen as a difference in flight time for any given payload, and is at best nominal. That is, for the most ambitious mission (Mariner spacecraft, orbit E) a 66 percent increase in power (15 kw to 25 kw) provides only a 7 percent decrease in flight time (1675 days to 1550 days). For the least ambitions mission (Pioneer

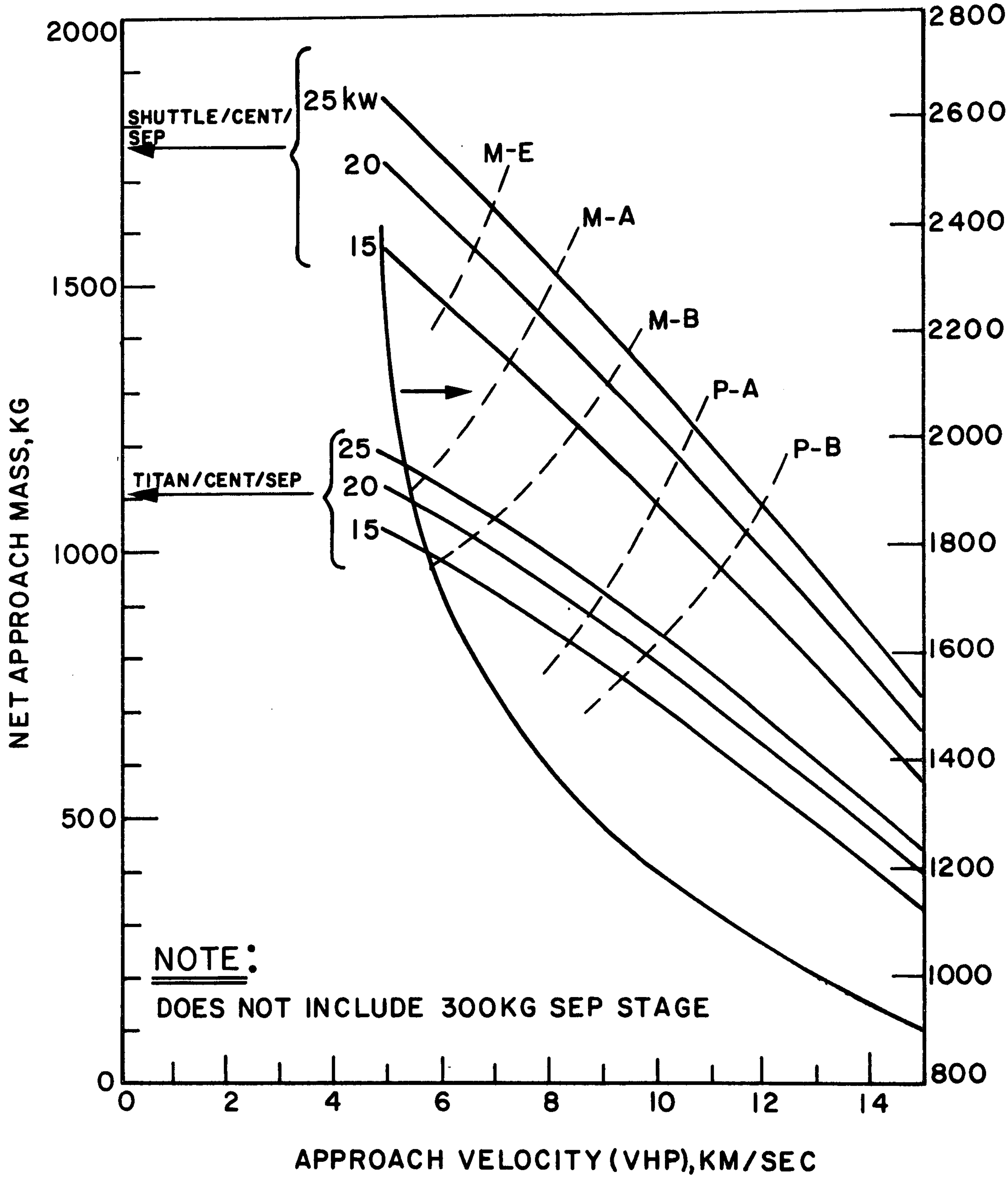


Figure 6-4 NET APPROACH MASS FOR SEP MISSIONS TO SATURN

spacecraft, orbit B) the same increase in power provides only a 2 percent decrease in time (1110 days to 1060 days). The performance of SEP (20 kw) in 1983, 1985 and presumably other years too, is within the range given by the 15 and 25 kw data in 1980.

In Table 6-1 a number of constraints and nominal values were chosen to do these trajectory calculations. The nominal conclusions are sensitive to some of these assumptions. In particular, the Tug, a proposed upper stage for the Shuttle, carries 75 percent more propellant than the current Centaur and still stays within the 65,000 lb Shuttle capability. The payload injected to earth escape is higher by about the same factor (Niehoff and Friedlander 1972) so that Mariner class missions could be performed ballistically during the 1980's. However, the Tug is unlikely to be available before 1983. A second area where the Shuttle may benefit is from a shortening or even removing the launch window requirement which typically results in a 200 kg increase in the Saturn approach mass. It would then be possible to do both Mariner missions with Shuttle/Centaur in 1982 and the B orbit in 1980 although in all cases the flight times are in excess of four years. With the assumption of no launch window the flight times for ballistic missions in 1985 are about 0.2 years longer than for SEP.

The solar electric data is sensitive to the mass of the SEP stage and to the power level. Reducing the power proportional weight to 20 kg/kw and raising the power to 40 kw, which is nearer optimum, would increase the approach mass by about 500 kg and reduces the flight time for the equatorial mission from 4.4 to 3.7. Flight time decreases are smaller for other missions. The solar electric data are subject to a small downward revision of about 3 percent in net approach mass to provide for a twenty day launch window, a much smaller penalty than was true for the ballistic transfers.

To summarize the nominal situation, the Shuttle opens new doors for Saturn orbiter missions by performing Pioneer class missions throughout the 1980's and Mariner missions in 1985. This is a significant advance over the standard Titan vehicles which are useful only in 1985 for Pioneer missions. Solar electric propulsion has the advantage of being far less sensitive to launch opportunity and delivers significantly higher payloads as well. A Titan based SEP system can be used for Pioneer class missions while a Shuttle launched SEP is needed for Mariner missions. Although either the development of a new chemical Tug or decreased launch window requirements will increase the Shuttle performance Mariner missions with a flight time between 3 and 4 years are not possible before 1983.

7. CONCLUSIONS AND RECOMMENDATIONS

A spacecraft orbiting Saturn can provide valuable data on atmospheric structure and circulation patterns, the magnetosphere and on surface features of the satellites which cannot be obtained from earth-based observations or from flyby spacecraft. Useful data can also be gathered on the ring system, the body structure of Saturn and atmospheric composition. Candidate science instruments were defined which could acquire the desired data. Many were based on designs used on previous planetary missions including Pioneer 10 and Mariner 9. Among the instruments in this group are the television system, the photopolarimeter, the magnetometer and the charged particle detectors. The concepts for the multi-element line scanner and the combined plasma wave and radio astronomy experiment were derived from earth-orbital instruments. Further study of objectives and/or instrument designs are required for infrared spectroscopy, microwave measurements and micrometeoroid composition detection.

From this list of candidate science instruments two payloads were selected. The first emphasized observations of the atmosphere of Saturn, the rings and the satellites using visual and infrared thermal imagery and ultraviolet and infrared spectroscopy. The second payload had a complete package of fields and particles experiments along with spin scan visual imagery and infrared radiometry. Because of weight and power constraints,a payload including all instrument is not practical.

Three orbits were identified as particularly useful from a scientific viewpoint. The first maximumized phase angle coverage by using the orbit plane including the subsolar direction. Nominal period of 30 days was selected along with 3.0 R_s for the periapse. The second orbit used a low, 1.6 R_s, periapse with the plane selected to prevent crossing the ring plane at less than 3.0 R_s. To maximize the number of satellites that are encountered at close range, an equatorial orbit with a 15 day period was selected. The first orbit is best for atmospheric and ring system observations and second best for the magnetosphere and satellites since Titan encounters can be arranged. The second orbit provides the best spatial coverage of the magnetosphere. The equatorial orbit is not useful for ring observations. Should there be hazard due to ring particles at distances beyond 3.0 R_s, then it will be necessary to increase the periapse radii of these orbits appropriately. Microwave observations of Saturn have not established the presence of radiation belts, but the upper limits are consistent with the nominal model for Jupiter's trapped particles. A spacecraft with a periapse of 3.0 R_s or more can survive for at least ten orbits in the nominal environment. Because the rings cut off the belts at 2.3 R_s, a periapse of 1.6 R_s can also be used. For a worst case analysis, a periapse of four Saturn radii is appropriate. Attempts to improve our knowledge of Saturn's rings, magnetic field and radiation belts prior to the MJS '77 flyby are recommended as a method of permitting earlier final design work for an orbiting spacecraft.

Both the Mariner and Pioneer spacecraft can be considered for Saturn orbiter missions. The net mass (excluding propulsion) of a Mariner spacecraft which can provide data storage for 5×10^8 bits, data transmission at 45 kbps and ± 0.8 mrad pointing for the first science payload is estimated to be 608 kg. Most subsystems would be very similar to the MJS '77 ones. It was assumed that a space-storable retro propulsion with a specific impulse of 375 would be available in the 1980's. The larger propulsion system would require structural changes similar to the difference between 1969 Mars flyby and the 1971 orbiter. A proposed MJS '77 revision of the radio system was assumed which would improve its scientific capabilities and decrease its weight.

To convert the Pioneer spacecraft to an orbiter which can support the second science payload requires some major changes. A maximum data rate of 12 kbps is provided by a new 10 w X-band transmitter and storage is increased to 3×10^5 bits. Two MHW RTG's are employed to achieve 240 w of spacecraft power at end of mission. Structurel changes caused by the larger power source and orbit capture propulsion system bring the net mass in orbit to an estimated 312 kg (excluding propulsion).

Both ballistic and solar electric interplanetary transfers were analyzed for three selected launch years (1980, 1982, and 1985). Flight times of less than three years are not practical because of the large ΔV required for orbit insertion. The payload returns are marginal for flight times in excess of four years so that allotting one year for orbit operations gives a total mission time of five years.

A Pioneer spacecraft can be launched to Saturn by a Shuttle/Centaur/HE BII or a Titan IIIE/Centaur/SEP any time in the 1980's. To do the same for a Mariner spacecraft requires a SEP upper stage for the Shuttle/Centaur launch vehicle. Ballistic trajectory requirements decrease significantly from 1980 to 1985, but are roughly constant from 1985 to 1988. In 1985 it is possible to perform some Mariner missions with the Shuttle/Centaur/HE BII. However, to reduce the flight time below four years will require either eliminating the launch window penalty or utilizing the full Shuttle capability by developing the Tug. Further definition of the upper stages which can be lifted into earth orbit with the Shuttle is an essential prerequisite to further study of Saturn orbiter missions.

7.1 The First Program for Saturn Orbiters — A Baseline

In selecting a baseline program for Saturn exploration with orbiting spacecraft it is assumed that the nominal environmental models for the rings and radiation belts are adequate and that an appropriate launch vehicle is available for all missions. It is obvious that one spacecraft cannot complete the task of observing all components of the Saturn system. The ideal program would employ one spacecraft in each of the three candidate orbits. Mariner spacecraft with the first science payload whould be used in the maximum phase angle coverage and equatorial orbits. Either a Pioneer spacecraft with payload #2 or a Mariner with fields and particles instruments substituted for some of the payload #1 experiments (such as the IR spectrometer) could be used on the minimum periapse orbit. A less ambitious but less costly program can be based on two similar Mariner spacecraft with different sets of science instruments for the maximum phase angle and minimum periapse radius orbits. This pair of orbits is preferred since the equatorial mission requires the longest flight time and the largest retro propulsion system.

The Mariner spacecraft gets the nod over the Pioneer because its science instruments can provide better imagery and spectroscopy of Saturn's atmosphere and its satellites, and because fewer of its subsystems must be altered to do orbital missions. Using the Mariner does tie the missions to the development of the Space Shuttle and establishes 1980 as the earliest possible launch opportunity. For launches between 1980 and 1983 the data from the MJS-77 flyby of Saturn would not be available during the design of the spacecraft. Thus it might be prudent to delay the first Saturn orbiter to 1985 so that the flyby experience could be used to full advantage.

Between 1985 and 1988 adequate payloads are obtained with either solar electric or ballistic trajectories. The illustrations in Section 4 show that the good coverage of Saturn and the rings is obtained from the orbits of 1985 missions.

7.2 Comparison with Jupiter Orbiters

Because the spacecraft requirements for Jupiter missions are somewhat less demanding, the proposed Saturn orbiters should function well if placed into orbit about Jupiter. If identical performance at Jupiter were desired then it would be possible to cut the transmitter power by 50 percent and perhaps to use less redundancy since the life expectancy required is three years instead of five. A typical Jupiter orbit which is compatible with the nominal models for the radiation belts has a periapse of 4.0 R_j, a period of 30 days and for a typical approach velocity of 6.5 km/sec requires a ΔV of 1.64 km/sec. This is only slightly smaller than the ΔV's for Saturn orbiters. Thus the differences between a Jupiter orbiter and a spacecraft that can orbit either planet are relatively minor.

Perhaps the most significant difference is timing. After the Pioneer 10/G missions the extent of the radiation belts around Jupiter will be known and planning for an orbiter could begin. A current launch vehicle, the Titan IIIE/Centaur/BII, would be used for a Pioneer Jupiter orbiter in any launch year but can't do a Mariner mission until 1981-82 (IITRI/Astro Sciences 1972). Thus Pioneer missions could be launched as early as 1978 and Mariners in the early 1980's probably using the Shuttle. Since this is much earlier than the 1985 date proposed for the baseline Saturn program, the Saturn spacecraft will be derived from one which has orbited Jupiter. However, in future studies consideration should still be given to a single program for orbiters of both planets to be launched in the early 1980's using Mariner spacecraft.

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