William H. Pickering

The Grand Tour

1977 presents a rare opportunity for a single spacecraft to fly by Jupiter, Saturn, Uranus, and Neptune

During 1969, two Mariner spacecraft flew past Mars at an altitude of 2,130 miles and returned excellent scientific data, photographs, infrared and ultraviolet spectra, and infrared radiometer data. Furthermore, the trajectories were calculated with such precision that atmospheric refraction could be measured and our knowledge of the gravitational field of Mars refined. These flights are a measure of the present capabilities in planetary exploration. We are able to send relatively complex instruments to the nearer planets, operate them remotely and precisely, and return data to earth reliably and at a reasonably high bit rate.

By the data already obtained from planetary spacecraft missions, our knowledge of the solar system has greatly increased. However, it is clear that solar system exploration is just beginning. The few flights of the 1960s have merely touched on the exciting possibilities of new and varied scientific discoveries, and it is difficult to imagine a space program that does not devote a large share of its resources to planetary missions. The decade of the 1970s must assuredly become the decade of planetary exploration.

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Many studies by scientific groups concerned with the future direction of the space program have stressed the need for a concerted program of planetary exploration. The most recent of these, the Space Task Group Report to the President, September 1969, recommended

> that this Nation accept the basic goal of a balanced manned and unmanned space program conducted for the benefit of all mankind.
>
> To achieve this goal, the United States should emphasize the following program objectives: . . . increase man's knowledge of the universe by conduct of a continuing strong program of lunar and planetary exploration, astronomy, physics, the earth and life sciences.
>
> As a focus for the development of new capability, *we recommend* the United States accept the long-range option or goal of manned planetary exploration with a manned Mars mission before the end of this century as the first target.

In the text of the report it is stated that the program should be "unmanned planetary exploration missions continuing throughout the decade, both for science returns and, in the case of Mars and Venus, as precursors to later manned missions. The program should include progressively more sophisticated missions to the near planets as well as multiple-planet flyby missions to the outer planets in the late 1970's. Early missions to the asteroid belt and to the vicinity of a comet should be planned."

The Space Agency is thus given a mandate to expand its planetary program. It is to be hoped that the Congress will support this important scientific objective.

Of the nine major planets in the solar system, only three—Venus, the Earth, Mars—have been observed from spacecraft, and only Earth has been thoroughly observed. Unmanned journeys to Mars and Venus, while complicated technical missions, are nevertheless relatively easy when compared with the problems involved in traveling to Pluto or Neptune. However, the technical capability to send a spacecraft to the outer edge of the solar system now exists, and in the next decade such missions will be undertaken.

The journey across the solar system will involve a distance of many hundreds of millions of kilometers and will take several years. The target planets are relatively isolated because of the vast distances separating their orbital paths. Since only very minor perturbations to its free flight are possible for a spacecraft after it leaves the launching rocket, it is essential that the position and velocity of each of the planets be accurately known, and also that the gravitational field throughout the solar system be calculable. Astronomical observations over many years have established the planetary ephemerides with reasonable accuracy. The scale of distances in the solar system is established by the Astronomical Unit, defined as the mean distance between Earth and Sun. Observations of the motion of

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mean distance from Sun (A.U.)	0.4	0.72	1.00	1.52	5.2	9.5	19.2	30.1	39.5
Sidereal period (years)	0.24	0.61	1.00	1.9	11.9	29.5	86.0	164.8	
Eccentricity of orbit	0.206	0.007	0.017	0.093	0.048	0.056	0.047	0.009	
Inclination of orbit	7°00′	3.39°	—	1.85°	1°18′	2°29′	0°46′	1°46′	
Equatorial radius (Earth = 1)	0.38	0.95	1.0	0.53	11.2	9.5	3.7	3.9	
Mean density	5.0	5.1	5.52	3.9	1.33	0.70	1.7	1.6	

Table 1. Properties of the Planets

Astronomical Unit	149 597 893 ± 5 km 499.004788 ± 0.000015 light-seconds
Ratio of masses of Sun and Earth	332,945.6 ± 0.3
Ratio of masses of Sun and Venus	408,522 ± 3
Ratio of masses of Sun and Mars	3,098,700 ± 100

Table 2. Some Solar System Constants

satellites around the planets and of the planets' perturbing effects on each other's motion have allowed their masses and gravitational fields to be ascertained. Table I lists some of these properties of the planets.

From the point of view of the planetologist, the planets of the solar system can be divided into two groups—terrestrial planets and outer planets. Table I shows that the planets Mercury, Venus, and Mars have an average density rather like that of the Earth. The planets that lie beyond Mars have a much smaller average density.

The relatively small amount of information about the outer planets that has been obtained through observations made from the Earth is just enough to make it clear that much of the history and evolution of the solar system will only be revealed when these planets are better understood. For example, some questions which need to be answered are: Do Jupiter and Saturn radiate more energy than they receive from the Sun, and if so, why? Why are there two, or possibly three, rotational periods associated with different parts of Jupiter? What is the nature of the red spot? What is the nature of the rings of Saturn? Why does Uranus have a spin axis almost in the plane of the ecliptic? What is the composition of the atmospheres of these planets? Do these planets have a solid surface? How can the various collections of satellites be explained?

The answers to most of these questions can be obtained only from data taken in the vicinity of the planet. Spacecraft passing near it can observe the planet in many parts of the spectrum, and relay the data back to Earth. The first flights are expected to be simple flyby missions which make close observations for only a few hours. Later missions, by remaining in orbit around the planet, or possibly by landing on a suitable satellite, can continue observations for long periods of time and observe secular changes. Still other missions may send a probe or capsule into the atmosphere and make direct measurements.

Trajectory calculations for interplanetary flights must be of extraordinary accuracy, and must be made with modern high-speed computers. For the inner planets, recent radar and spacecraft observations have provided sufficiently accurate data of the gravitational fields and the scale of distances to permit precise trajectory calculations (Table II). The data for the outer planets however are not of this accuracy, and must be refined by actual spacecraft flights.

Rough approximations of the energies and times associated with flights to the outer planets can be made from first principles. The spacecraft must be launched from the Earth so as to exceed the escape velocity. The excess velocity is usually described by a parameter, C_3, which is twice the excess kinetic energy per unit mass, or simply the excess velocity squared. Since the Earth moves in its orbit at a speed of about 30 km/sec, and since its orbit is approximately circular, a heliocentric velocity of $\sqrt{2} \times 30$ or 42 km/sec will be just sufficient to escape from the solar system. Hence, a spacecraft launched with $C_3 = 144$ km^2/sec^2 could escape from the solar system, provided that its direction of travel away from the Earth was in the direction of the Earth's motion around the Sun. This spacecraft would take about 45 years to attain a distance equivalent to the orbit of Pluto.

In order to travel from the Earth's orbit to that of one of the outer planets, the minimum energy required will be somewhat less than this value and will be associated with an elliptical trajectory having its perihelion at the Earth's orbit and its aphelion at the orbit of the target planet. The equation for such an ellipse can be written

$$V_0^2 = K\left(\frac{2}{r_o} - \frac{1}{a}\right)$$

V_o is the perihelion velocity, r_o the corresponding perihelion distance, a the semimajor axis of the ellipse. Hence, for an ellipse with perihelion at 1 A.U. and an aphelion at the distance of Uranus, we have

a = 10 A. U.
r_o = 1 A. U.
$V_o = \left(\frac{19}{10}\right)^{1/2} V_E$ where V_E is the velocity of the Earth in its orbit
= 41.3 km/sec
$\therefore C_3$ = 128 km²/sec²

The time required to reach aphelion can be easily calculated since the period of an elliptical orbit varies as $a^{3/2}$. For a = 10 A.U., the half period is, therefore, 15.7 years.

Travel to the outer planets will require launching rockets with capability sufficient to give the spacecraft C_3 values lying in the general vicinity of 100–150 km²/sec². As a comparison, the energy required to travel to Mars in 1969 was C_3 = 16 km²/sec².

Six years ago, Minovich (*7*) first showed that planetary missions could be made more efficient by using near encounters with other planets to change the heliocentric trajectories. This so-called gravity assist technique is of great value for journeys beyond the planet Jupiter. The principle of the method is simply to change the heliocentric velocity of the spacecraft by using a planet to perturb the trajectory in a desired fashion. As seen from the perturbing planet, the spacecraft motion is along a hyperbola. The asymptotic speed on both incoming and outgoing parts of the hyperbola will be the same, but the spacecraft velocity vector will be turned through an angle which is a function of the asymptotic speed, the gravitational constant of the planet, and the distance of closest approach. The heliocentric motion will therefore show a change in both direction and speed. The spacecraft will have changed its heliocentric energy. The new energy may be either greater or less than the original energy.

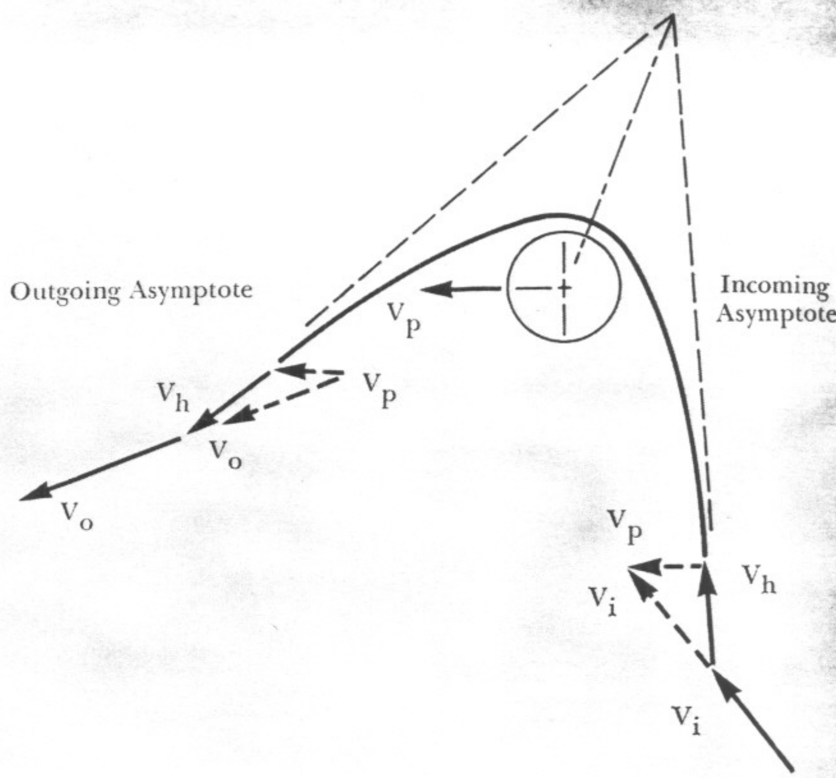

Fig. 1. Encounter hyperbola

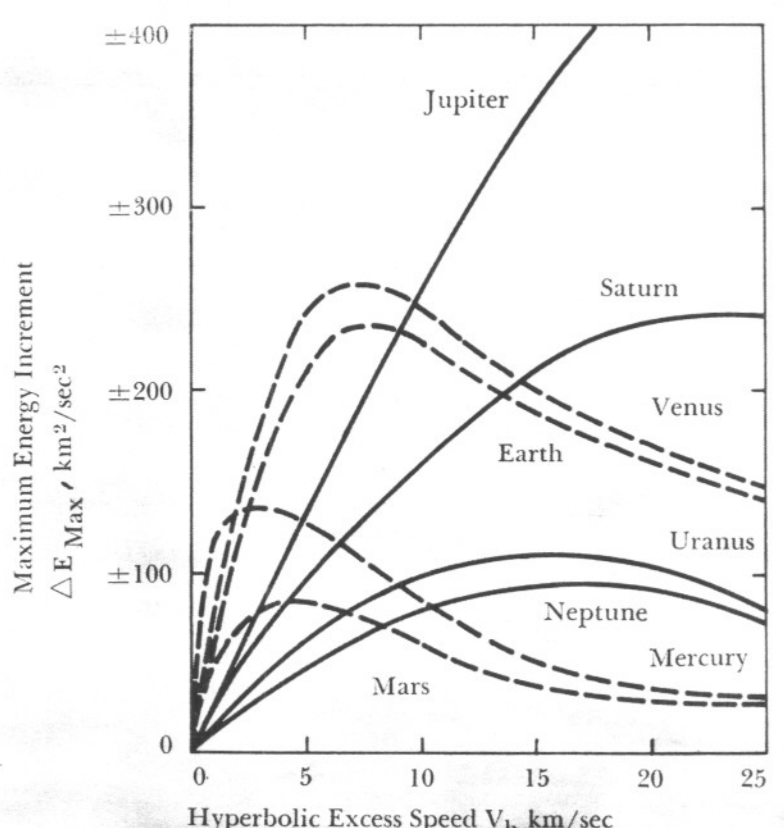

Fig. 2. Maximum energy increment vs. hyperbolic excess speed of spacecraft

Figure 1, adapted from Flandro (2), illustrates the geometry of such an encounter. It is easy to show that, neglecting the motion of the planet during the encounter, the change of energy experienced by the spacecraft is

$$\Delta E \leq 2 v_p v_h,$$

where v_p is the speed of the planet and v_h the asymptotic spacecraft speed as seen from the planet. The maximum energy change cannot be obtained in practice because it requires a 180° change in spacecraft direction and, therefore, passage of the spacecraft through the center of mass of the planet. When the distance of closest approach is made the equatorial radius of the planet, the maximum energy increment obtainable is as shown in Figure 2.

Jupiter, because of its large mass, is very effective at changing spacecraft trajectories, even when the relative velocity is quite high. Hence, when the other outer planets are in the correct positions relative to Jupiter, it becomes possible to use the gravity assist of Jupiter to reduce both the launch energy requirements and the time of flight to these planets. The period from 1976 to 1980 is a very favorable opportunity for such missions. In fact, 1977 offers the possibility of a four-planet mission, Jupiter-Saturn-Uranus-Neptune. The possibility of this mission, familiarly known as the Grand Tour, occurs at 175-year intervals.

Other opportunities during the last half of the seventies include three-planet missions such as Jupiter-Uranus-Neptune or Jupiter-Saturn-Pluto, and numerous two-planet missions, which occur more frequently. For example, since the period of Jupiter is about 12 years, the two-planet opportunities using Jupiter for gravity assist repeat at approximately this interval. Actually, the Jupiter-Uranus mission repeats about every 14 years, while the Jupiter-Saturn opportunities are spaced at about 20-year intervals.

As an example of the value of the Jupiter assist, the Jupiter-Uranus mission requires about six years instead of the 16 required for the direct minimum energy mission. The launch energy required is slightly less.

Because of this marked decrease in travel time, the Jupiter gravity assist trajectories are obviously the preferred method of sending spacecraft to the outer planets. An engineering difficulty which this introduces is the requirement that the flight path near Jupiter be very precisely located with respect to the planet. However, the demonstrated performance of the 1969 Mariner spacecraft is evidence that adequate guidance accuracies can be attained. If necessary, after passing the planet, the trajectory can be modified slightly with a flight path correction maneuver similar to that used on the Mariner missions.

The selection of a set of missions which will serve to initiate the exploration of the outer planets requires a detailed analysis of possible trajectories to determine those which best match the requirements of the science instruments, the launching rocket, and the spacecraft performance. As an example, Figure 3 shows some of the constraints associated with a Jupiter-Saturn-Pluto mission. A launching in 1976 requires the lowest energy, but flies the spacecraft close to the surface of Jupiter if the flight time to Pluto is to be kept short. In 1977, the situation is improved. Flights in 1978 or 1979 will require

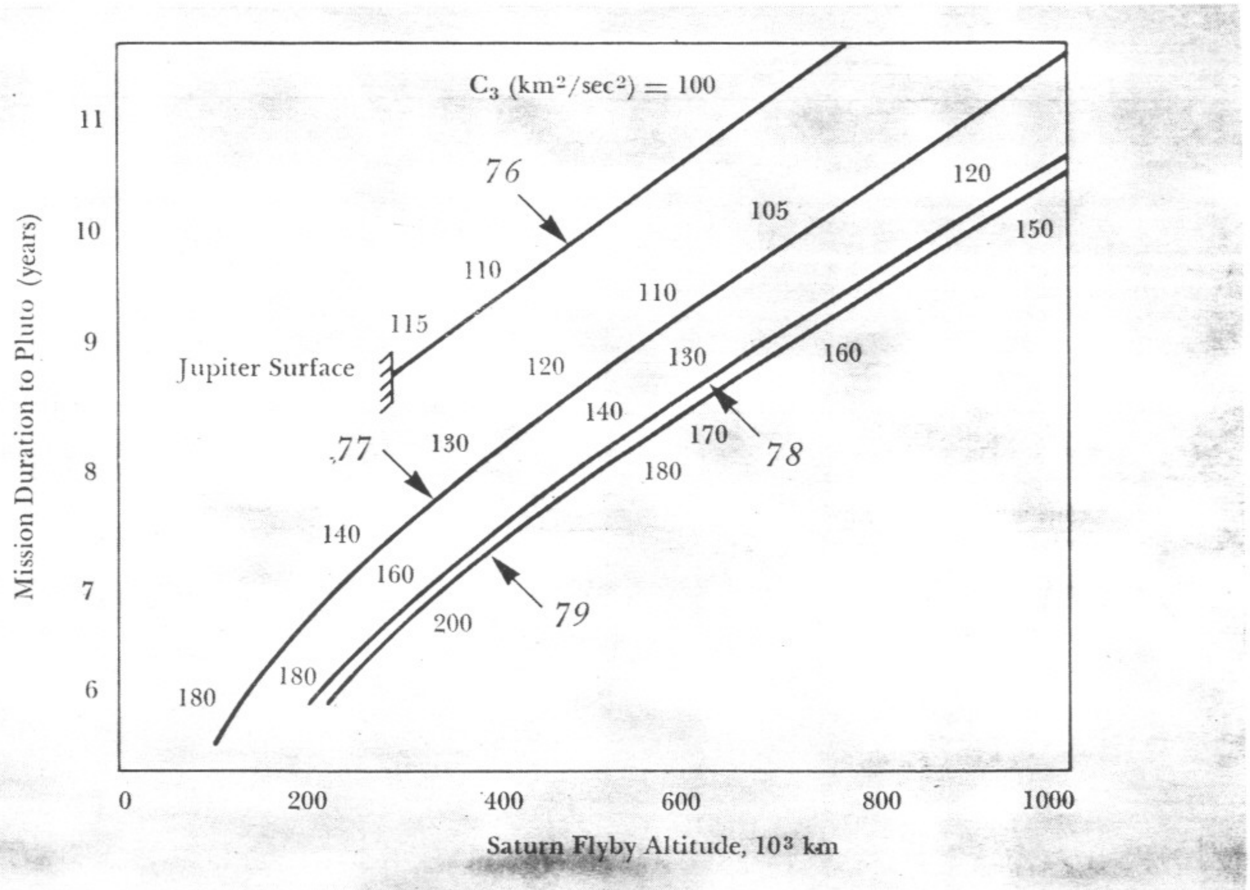

Fig. 3. Earth-Jupiter-Saturn-Pluto constraints (21-day launch period)

greater launch energies. Hence, 1977 appears to be the best year.

Figure 4 lists a rational set of missions which should be performed in this period. The first flight, in 1974, would serve as a precursor, testing the spacecraft design and performance, and evaluating the engineering solutions for such a mission. At the same time, it would obtain valuable information about Jupiter and also the environment encountered in the asteroid belt and in the vicinity of Jupiter. Meteoritic dust in the asteroid belt might present a hazard to a spacecraft. The radiation field near Jupiter will almost certainly be a problem to some types of instruments and electronic equipment. It must be measured as a function of location near the planet. The next mission, the Jupiter-Saturn-Pluto flybys, would be launched in 1977, with Pluto encounter in 1986. Data from the 1974 flight would be available in time to modify either the spacecraft or the mission plan if this proved necessary. In 1979, when the earlier mission had passed Jupiter, the third mission, the Jupiter-Uranus-Neptune flights, would be launched. Neptune would be reached in 1988.

The follow-up flights of Part II are more ambitious missions. Orbiters can use the same basic spacecraft as for Part I, suitably modified with additional propulsion capability. The probes which enter the atmospheres of these major planets are required to survive much greater entry velocities than those encountered in lunar return to Earth. Since missions to Jupiter can be launched every year, the probe and orbiter missions proposed for 1978 and 1980 could be scheduled for other dates if necessary. The Saturn and Uranus probes are best launched in the early 1980's, using a gravity assist from Jupiter. If they cannot be ready at that time, the next opportunities will occur around 1990 for Uranus and 2000 for Saturn.

Scientific instruments which would be suitable for the Part I missions are shown in Figure 5. Taking this as a typical list, a total instrument weight of the order of 100 pounds would be sufficient to provide a significant mission. An attitude-controlled spacecraft is required so that the instruments can be oriented in specified directions. Certain instruments will have to be mounted on a movable platform in order to observe the planet during the near encounter phase of the flight.

Figure 6 illustrates the proposed spacecraft. The dominant feature is the parabolic antenna, which must unfold after launching and which remains accurately pointed toward Earth. Power for the spacecraft is generated by a radio isotope thermoelectric generator (RTG) located at a distance from the science instruments in order to avoid radiation problems. The planetary instruments are placed on a movable scan platform. Two magnetometers are mounted on 30-foot booms to avoid spacecraft magnetic disturbances. The spacecraft weight is 1,250 pounds.

As an example of the geometry of a typical planetary encounter, Figure 7 illustrates a flight past Jupiter. Note that the planetary instruments on the scan platform must be rotated through more than 180° in order to keep the planet in view. Both the sunlit and the dark hemispheres are observed.

Part I: Initial survey of the outer planets

- 1974 Jupiter flyby
- 1977 Jupiter-Saturn-Pluto flybys
- 1979 Jupiter-Uranus-Neptune flybys

Part II: Follow-up exploration

- 1978 Jupiter flyby/entry probes
- 1980 Jupiter orbiter
- Saturn flyby/probes—Uranus flyby/probes

Fig. 4. Mission summary

Magnetometer (DC and AC fields)	6 lbs
Plasma probe	8
Cosmic ray telescope	6
Trapped radiation detector	6
Decameter radiation detector	4
Imaging (high and low resolution)	50
Infrared radiometer	10
Ultraviolet photometer/spectrometer	10
	100 lbs

Fig. 5. Typical science payload

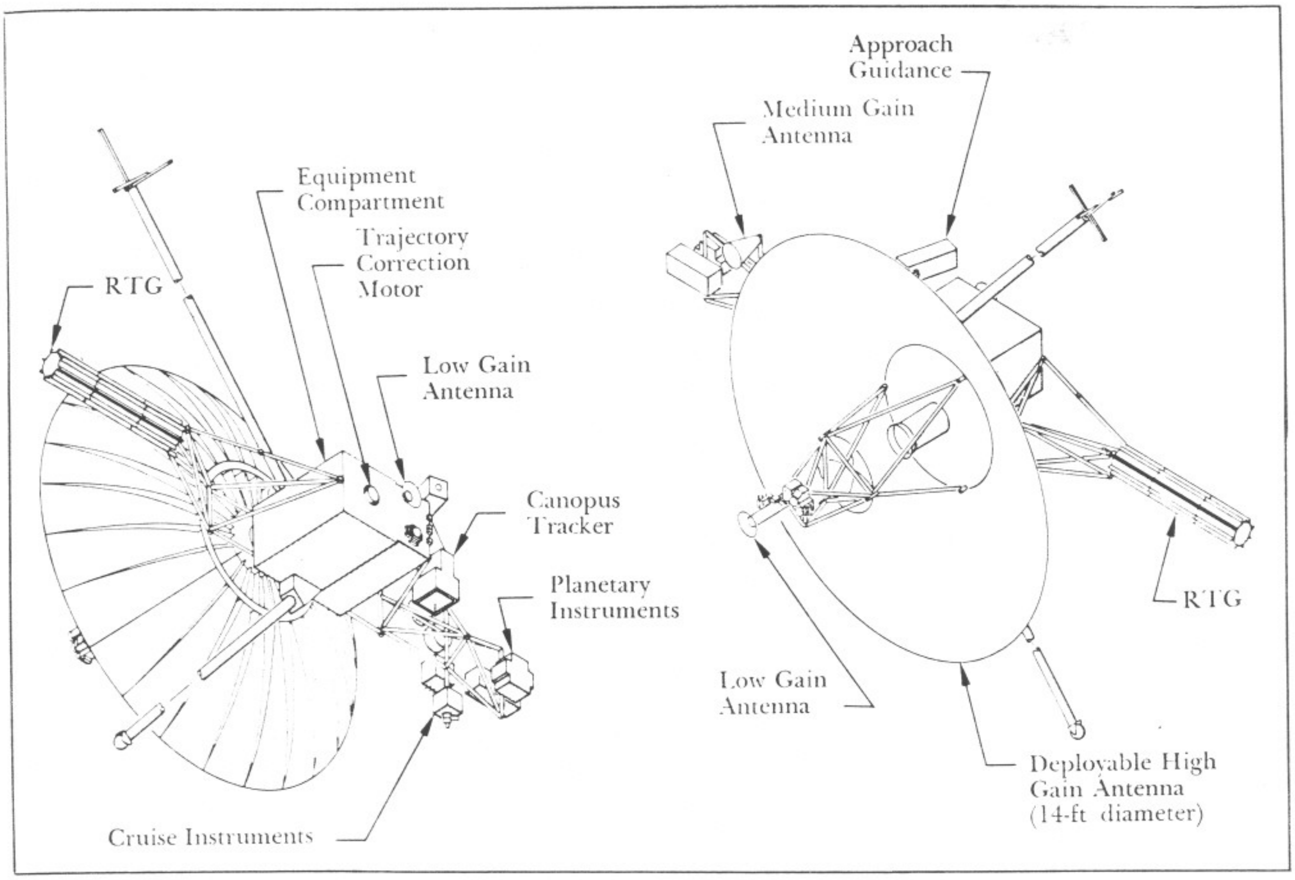

Fig. 6. Proposed outer planet spacecraft

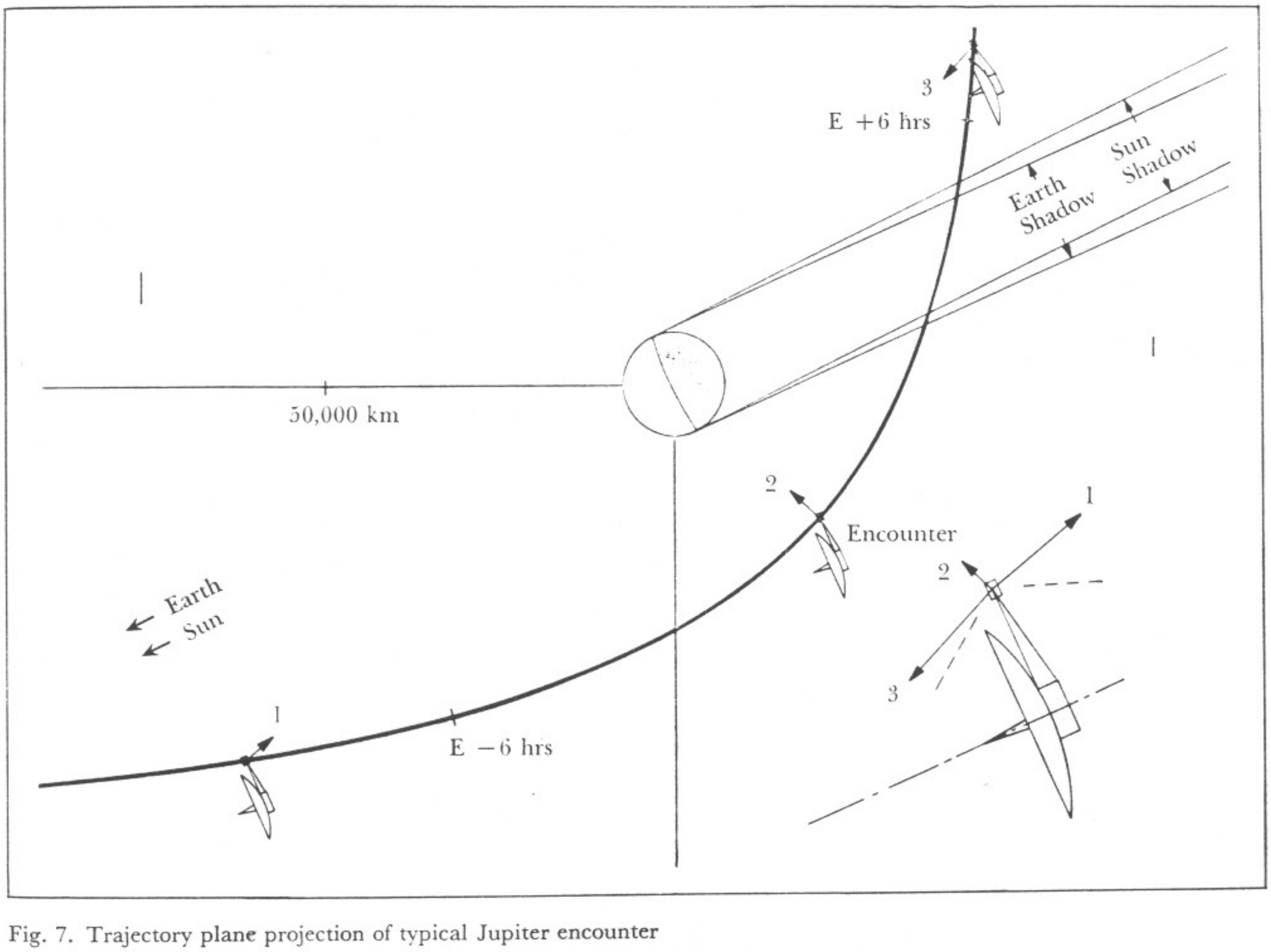

Fig. 7. Trajectory plane projection of typical Jupiter encounter

Communications from the outer planet spacecraft will be conducted at X-band with a 20-watt transmitter and a paraboloid antenna 14 feet in diameter. On the ground, the 210-foot antennas which will shortly be operational in California, Spain, and Australia will be the prime receiving antennas. The system will have a data rate of 2,000 bits per second at Neptune and Pluto, and 128,000 bits per second at Jupiter (Fig. 8). Compare these rates with Mariner 1969, which transmitted at the rate of 16,200 bits per second from Mars.

The launch vehicles which will be available for these missions include Titan III and Saturn V. Figure 9 compares their capabilities as a function of C_3. For spacecraft in the weight range from 1,000 to 1,500 pounds, and for C_3 about 120 km^2/sec^2, the Titan IIID/Centaur/Burner II is a satisfactory vehicle.

Table 3 gives a summary of the Part I program. The closest approach altitudes are given in planet radii. This program is quite feasible and realistic. The engineering problems are understood and, for the most part, solutions already exist. The scientific interest is very great. For the first time, it has become possible to make detailed observations of the rings of Saturn and the red spot of Jupiter. The magnetic fields of these planets will be measured directly; the radiation belts surrounding them will be charted. The thermal balance of Jupiter and Saturn will be determined. The nature of the cloud cover and perhaps of the surface of all the outer planets will be investigated. En route to the planets, the outer fringes of the solar wind and the interplanetary magnetic field will be observed. The true galactic field and the galactic cosmic ray flux may be measured.

The Grand Tour is truly one of the most significant scientific investigations in history. As with all explorations into uncharted regions, we do not know what new data will be returned, but we do know that they will immeasurably enhance our understanding of the solar system.

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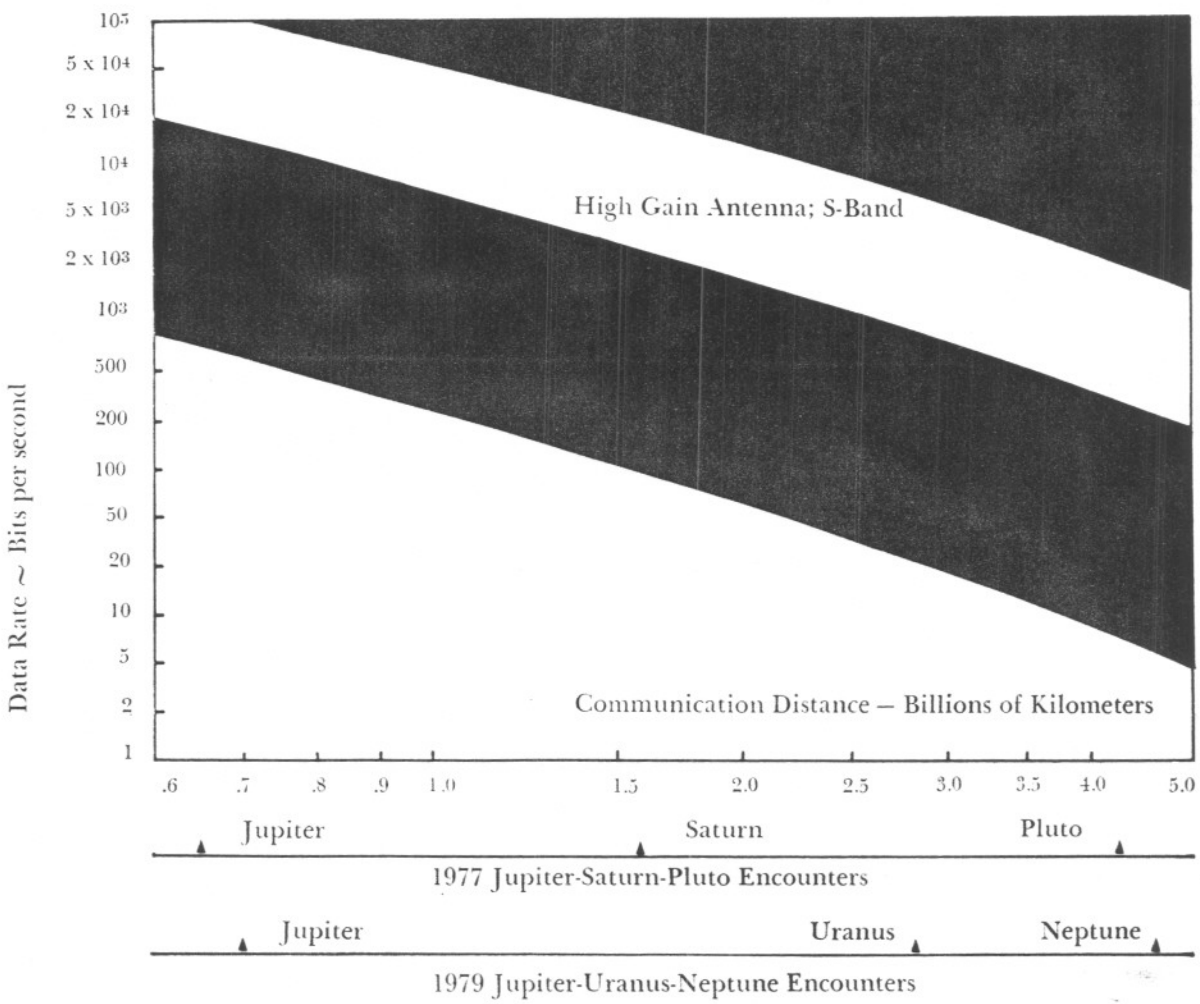

Fig. 8. Data rate vs. Earth-spacecraft distance

	Altitude	Flight time (years)
1. 1974 Jupiter flyby		
One launch May '74		
Jupiter encounter	Open	1.4
2. 1977 Jupiter-Saturn-Pluto		
Two launches Sept. '77		
Jupiter encounter	3.2 RJ	1.4
Saturn encounter	7.5 RS	3.0
Pluto encounter	Open	8.5
3. 1979 Jupiter-Uranus-Neptune		
Two launches Nov. '79		
Jupiter encounter	5.8 RJ	1.5
Uranus encounter	1.1 RU	5.7
Neptune encounter	Open	9.1
4. Launch vehicle Titan IIID/Centaur/Burner II (2330);		
C_3 and maximum S/C weight: 120 km²/sec² for 1,435 lbs.		

Table 3. Mission mode

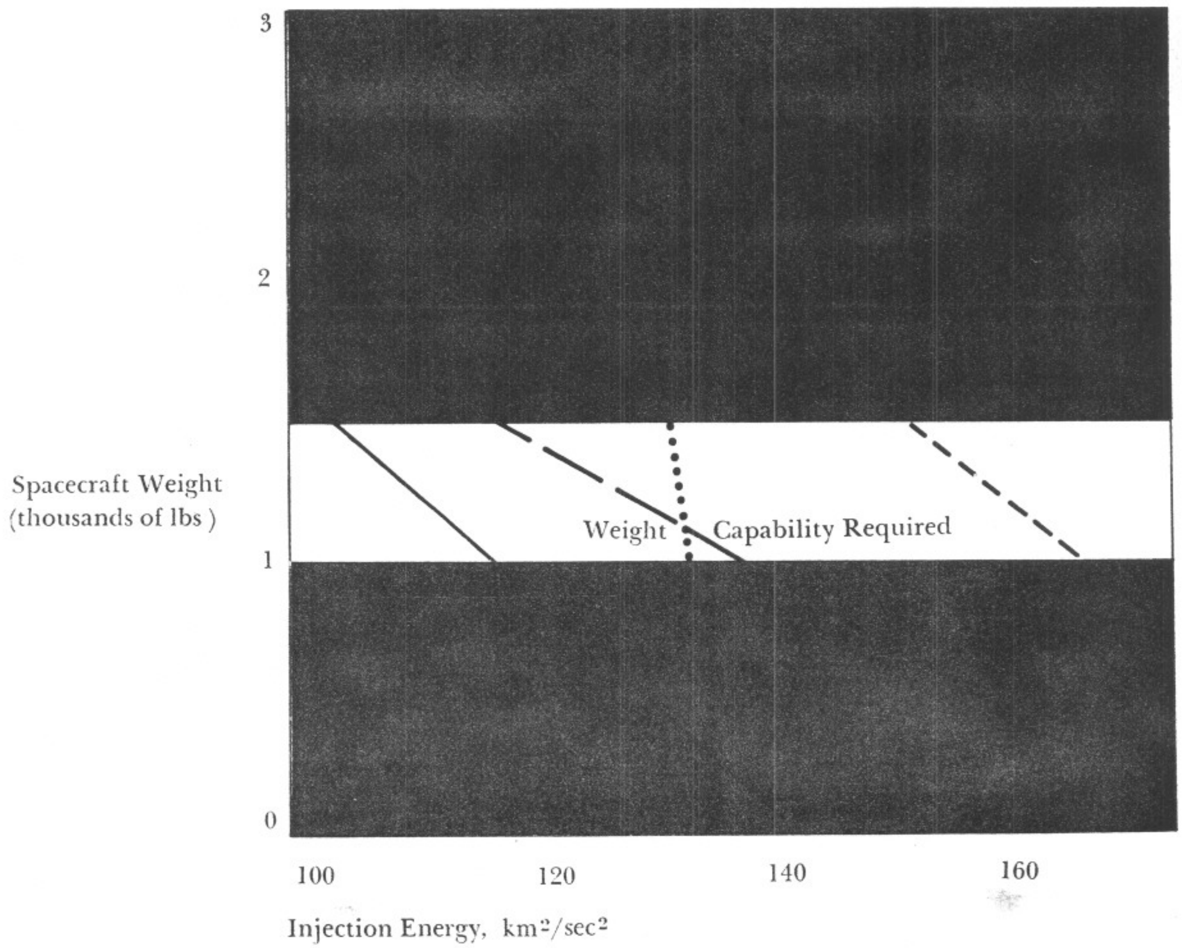

Fig. 9. Launch vehicle capability comparison