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THE OUTER PLANETS: GETTING THERE FAST*

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Abstract

The terrestrial planets and small bodies of the **inner solar** system provide many opportunities for meeting the NASA criteria of faster, better, and cheaper. The challenge remains, however, as to how the outer planets and their related bodies can be made to satisfy this new paradigm. in this paper, a brief review is given of NASA's outer planet missions as performed with chemical propulsion systems. The limitations in delivered mass and short flight times are clear. Ion propulsion, on the other hand, with 10 times the efficiency, can perform outer planet missions on par with those conducted for the inner planets with chemical systems. Flight times can be.5 years or less.

The Kuiper Express is discussed as an illustration of the integrated approach that should be used in mission and spacecraft design to maximize science return. For fast missions to the outer planets, low mass spacecraft is an important requirement if medium size launch vehicles, such as the Delta II 7925, are to be used. Assuming nuclear technology will not be available for power or propulsion, technology for solar sources must be addressed. Also, since fast transfers imply high arrival velocities, methods for deceleration needed for orbiter missions require development, such as aerocapture with ballut es. These technologies and others will be briefly discussed.

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introduction

In this era of smaller, faster, cheaper for solar system exploration, the outer planets should not be forgotten. The Voyager flybys of Jupiter, Saturn, Uranus, and Neptune returned spectacular results, including images of multi varied moons and planetary atmospheres, The public also was very receptive, being able to see whole new worlds race across the TV screen. The coming sequence of the Galileo spacecraft images of Jupiter and the Galilean satellites up close from 1996 to 1998 should bring home the fact that we live in a multicolored star system, where Mars, Venus, and even Earth is but one spectrum range of possibilities. Our quest for knowledge of solar system formation and evolution demands that a comprehensive NASA program be undertaken to include outer planet missions as a major part of solar system exploration.

The challenge set forth, then, is how missions to the outer planets can be made to fit the new paradigm. This paper addresses the most important requirement: "faster." Short flight times have many advantages, most of which have been applied to the Discovery program. Faster missions reduce cost. Assuming an acceptable launch vehicle is used, operations cost will be lower. Faster missions also means that new technologies, many unique to outer planet exploration, will be flight-proven sooner, increasing the pace of technology advances. Faster missions will return scientific data sooner, within acceptable times for graduate student participation, for example. Also, the faster that data is returned, the faster it may be used to complement stellar system formation and evolution knowledge and theories.

NASA Outer Planet Missions

The questions of better and lower cost missions also has to be addressed. The Pioneer and Voyager missions of the 70's and 80's were flyby missions whose spacecraft masses were modest, 260 kg and 825 kg, respectively. Still, using direct launch, they required Atlas and Titan III or IV launch vehicles, with Centaur upper stages. The current missions, Galileo now at Jupiter, and Cassini to Saturn (to be launched in 1997), are orbiters carrying entry probes, and have considerably higher mass. These both use gravity assist launch opportunities of Earth and Venus (and Jupiter for Cassini), and sizable retro-propulsion systems for orbit capture. Galileo's flight time to Jupiter was 6 years, and Cassini's to Saturn will be about 7 years. Galileo used the Shuttle/IUS launch, and Cassini will use a Titan/Centaur launch. in the future, smaller launch vehicles and faster flight times will result in lower cost. Mission capability, on the other hand, will increase due to smaller, more capable instruments; and development of technology for power, propulsion, orbit capture, communications, and entry systems.

The Kuiper Express Experience

A serious effort to design a modest mission which could reach the outer limits of the solar system was undertaken in 1994. Thousands of large icy bodies were postulated to exist in the region beyond Neptune's orbit by G. Kuiper in 1951[1]. The mission proposed would be a flyby of one of these newly (or yet to be) discovered bodies, and images and spectra taken by a small but very capable science instrument.

The approach taken by the Kuiper Express team was integration of science instrument and spacecraft systems in order to simplify development, operations, and minimize mass[2]. The mission goal of the Kuiper Express, based on trajectory possibilities, is to design a spacecraft capable of flybys of Uranus, Neptune (and Triton), and then out to a Kuiper belt object at about 40 AU. Restrictions on the design were that no nuclear power be used, and that launch be limited to the Delta II capability

integration began with the science instrument, an earlier version of which was developed for the Pluto Fast Flyby. Here, instead of accommodating several remote sensing instruments independently onto a spacecraft, each with their own power and pointing requirements, data rates, etc., the Pluto Integrated Camera Spectrometer (PICS) would use a single 30 cm mirror to transmit light to six sensors ranging from IR to UV. in the design, these are enclosed in a silicon-carbide structure to minimize weight (-5 kg), volume, and distortion, and maximize strength. Since the original design, modifications have been made to satisfy alternate specific mission requirements.

The next concern of the Kuiper Express team was the considerable drop in temperature as the spacecraft moves away from the sun. Since RTG's are not to be used, (although they were on all previous outer planet missions), reliance would be on large solar arrays which would provide 8.5 watts at 40 AU (15 kW at 1 AU). Specifically, these are concentrating arrays, folded for low volume, and deployed with an inflatable, rigidizing structure to minimize weight, The provider, Boeing Corp., conducted tests to show that the solar panels will provide this power under the conditions at 40 AU. This minimal power would be used to provide heat to the electronics enclosed in a "thermos bottle" enclosure, as well as for spacecraft functions and data return. Energy from this low power source would be stored in two 300 watt-hr NiCd batteries, one as a redundant backup, and used as needed.

Solar arrays would also be used in the first 2.5 years of launch to provide power for ion propulsion. This permitted the use of a Delta II launch vehicle, and no larger. To illustrate the effectiveness of solar electric propulsion, total velocity (ΔV) imparted to the spacecraft, referenced from low Earth orbit, is a good single parameter to use. Missions to Mars or Venus require a ΔV of about 3.6

km/s. With a chemical upper stage having a specific impulse Of 400 see, the propellant required is 60% of initial mass. A direct flight to Jupiter would require 6.4 km/s. Here, the propellant amounts to 80% of initial mass. For chemical propulsion to Jupiter, then, either a smaller spacecraft or a larger launch vehicle must be used. Using planetary gravity assist can alleviate this problem, but at the expense Of a more complex mission, with longer flight times, usually, and sometimes very limited launch opportunities.

With solar electric propulsion, On the Other hand, having a specific impulse Of 3000 see, the percentages Of propellant would be 12% to Mars, and 20% to Jupiter. These are for essentially Hohmann transfers. Expending additional propellant decreases flight time, particularly for the inter planets.

Beyond the Kuiper Express

The Kuiper Express design provides a starting point for fast missions to the Outer planets. It is based, though optimistically, on currently available technology. That is, the companies involved, Olin and Boeing, will commit to their design parameters for the power and propulsion systems.

Yet, 10 year missions cannot be considered fast. What needs to be done to remedy this problem? Taking spacecraft launch mass as the single most important parameter (the Kuiper Express launch mass is about 860 kg), consider flying a derivative spacecraft, say in 2010, directly to each of the outer planets with lower launch masses of 800, 600 and 400 kg, for comparison. Power is held at 15 kW (at 1 AU).

The results arc shown in Tables 1 and 2. It is immediately seen that flight time decreases are not particularly impressive for Jupiter, or even Saturn, but they are for Uranus and Neptune. Cutting spacecraft mass in half reduces Uranus flight time by about 3 years, and Neptune flight time by 5.5 years.

It should be noted in arriving at these results, that optimization Of the solar electric trajectory is not invoked. The optimization process usually involves maximizing launch mass **(less** propellant) for given power and propulsion parameters and for a given launch vehicle capability. This approach is necessary if the technology and hence the masses of the subsystems remain uncertain.

Table 1. **Flight** Times **to the Outer Planets**
(Power = 15 kW, Isp = 3000 see, Eff. = 0.7)
(Launch Vehicle = Delta II 79?5)

Mass(kg)	800	600	400
Planet	Flight Time (yr)		
Jupiter	1.15	0.94	0.73
Saturn	2.38	1.83	1.37
Uranus	5.69	4.00	2.84
Neptune	9.96	6.58	4.54

Table 2. **Delta-V and Mass Characteristics**
(Power = 15 kW, Isp = 3000 see, Eff. = 0.7)
(Launch Vehicle = Delta 11 79?5)

Mass(kg)	800	600	400
Launch C_3 (km^2/s^2)	26	38	62
Total ΔV(km/s)	14.0	16.2	21.2
Thrust T (days)	300	240	200
Prop. Mass (kg)	225	195	165
Dry Mass (kg)	575	405	235

Then, maximizing mass will allow greater flexibility in selecting structure, communication systems, and instruments to fit the available mass. This usually leads, in the optimization, to low launch energies (C_3), high launch mass, and use Of gravity assist trajectories to force the maximized mass to stay within a desired (usually long) flight time.

in Tables 1 and 2, specifying launch mass as fixed utilizes the maximum launch energy available by the launch vehicle. The result, with the lower masses shown, is that total ΔV increases, flight time decreases, and propellant usage remains at or below 40%. An additional result is that the thrust duration ranges from 200 to 300 days, with power ranging from 15 kW at launch to 1 kW at 3.9 AU, the cutoff distance. in a sense, the propulsion system is underutilized. Solar power available drops from 15 kW to 5 kW, for example, in about 3 months. For these fast, direct missions, thruster lifetime should not be considered a problem.

The Promise of New Technology

Having established that lower launch mass can considerably reduce flight time, especially for direct trajectories, it is necessary to consider how mass, in turn, can be reduced while maintaining or increasing spacecraft capability. Applying functional integration will help considerably, as it has for the computer industry. Also, the many advances made in non-space applications, such as light weight structures, may serve well in spacecraft design. Nevertheless, some new technologies, such as the inflatable Power Antenna, will require several stages of development and testing before it can satisfy all of the requirements for use in space.

Fortunately, in these days of stiff competition, many industries are attempting to reduce the time required to go from research to application. New analysis and production tools are available to make this happen, An example is solar cell materials, which have long been dominated by silicon. Today, research is producing many alternates for use[4], such as gallium arsenide, iridium phosphide, and others. Also, manufacturing methods are in place for stacked cells and concentrators which can yield efficiencies up to 40%. What is happening here can happen in other areas of technology. What is needed today is to identify what new materials and systems should be developed for outer planet missions in order to meet the required goals of better, cheaper, faster.

Electric Propulsion

Ion propulsion systems have been around in the NASA laboratories for almost 30 years. I bring this time, only a few missions have seen its use, and only in Earth orbit. Many studies have been done which consider applying them to difficult, deep space missions, such as multiple rendezvous of the main belt asteroids, or comet rendezvous. Today, with the planned launch of NSTAR in 1998, a conservative 5 kW system will be launched for, most likely, an asteroid or Come't flyby. This will be the first in a series of New Millennium technology experiments to be flown by NASA.

Meanwhile, activity is underway to develop alternate thruster systems which are light weight, less dependent on power processing, more robust (able to operate over wide ranges of power and specific impulse), and longer lived. Specifically, two technology paths are being taken. One is improvement in the NSTAR ion engine by reducing dry mass, and applying carbon-carbon grids for longer life. The other, and most promising, is further development of the Russian thruster with anode layer ('TAL) being tested at JPL and Lewis. This path allows high thrust density, which means that a single thruster can operate at, say, **7.5** kW of electrical power. If development proceeds as anticipated, the 'TAL system mass should weigh in at under 80 kg for a 15 kW requirement.

Power and Communications

in the Kuiper spacecraft design, the solar array power serves three purposes: first, to provide kilowatts of electricity required by the ion thrusters, second, to provide power at 40 AU, in the Kuiper belt, to maintain spacecraft operation and temperature, and third, to transmit data to Earth. In the Kuiper design, a separate rigid antenna was included for communications.

One problem remained. It was not possible to use energy available directly from 8.5 W for spacecraft housekeeping and also use power required to transmit data to Earth. Therefore, batteries weighing 24 kg had to be carried for storage and energy allocation. Specifically, 1 gigabit of data, compressed 3:1 would require 25 W for 4 hr/day, and for about 40 days, to completely transmit recorded data of the flyby of a Kuiper object.

A new technology now being considered at JPL called the Power Antenna would speed transmission of data by combining the power and communication functions. in this approach, a large inflated and pressurized antenna serve as a large, reflective surface which could be used both as an RF antenna, and as a collector of solar energy. The idea here is that the solar energy would impinge upon an array of solar cells, or other energy converter, while the RF transmission would be diverted to transmit or receive signals.

Using an inflatable structure with a large diameter would afford high data rates for outer planet missions, and presumably have low mass. in comparison with the Kuiper Express system, a 14 m diameter inflatable Power Antenna would produce 10 W of power which could transmit at a rate 4 times faster, or complete transmission in 10 days.

Such a power antenna has been built and tested by L'Garde, Inc. and will be flown this year on the Shuttle[5]. It will be a NASA INSTEP experiment deployed from a Spartan spacecraft. The 14 m diameter inflated reflector will be displaced from the Spartan, and oriented, using three inflatable struts. This will provide a focus distance from the reflector to light panels fixed to the Spartan. The goal of this experiment is to validate deployment, measure surface accuracy, and investigate structural clamping characteristics. The total mass of this inflatable antenna is high, (65 kg), but could be made much lighter. One estimate is 20 kg.

Looking further into the future, there is the promise of optical communications increasing the data rate more than a hundred fold. Around 2010, for example, it may be possible for a 10 W laser on the spacecraft at the distance of Neptune to transmit 100 kbits/s to Earth. This assumes a 30 cm aperture telescope on the spacecraft with precise Earth acquisition and pointing, and either a 10 meter Earth orbiting relay station, or a 10 meter 3-5 station ground based system of telescopes. The one gigabit of recorded data on Kuiper Express could be transmitted to Earth in less than 4 hours with this system.

Ballute Aerocapture for Orbiters

Fast flight times to the outer planets imply high velocities relative to the planet at arrival. These velocities would be acceptable for certain types of missions, such as flybys, which can yield Voyager class science, or for atmospheric probes, as carried cm the Galileo spacecraft. It is also possible to carry impact probes for the Moons, so that sensors on the flyby spacecraft will determine composition and other surface characteristics from the dust and gas released. Many applications would require autonomous navigation, which is a technology currently being pursued at JPL.

Extensive examination of the planet and the satellites, however, will require orbit capture. Galileo and Cassini use chemical retro-propulsion. This can be done reasonably well at Jupiter and Saturn for direct missions of 3 and 5 years, respectively. The increased mass to carry the retro-propulsion system could be offset somewhat by the reduced mass of the lower power and smaller electric propulsion systems suitable for the longer flight times.

For Uranus and Neptune, alternate means of orbit capture are needed if flight times are to be kept low. Aerocapture, i.e., using the atmosphere of Uranus or Neptune to slow down, seems to be the only effective way of achieving orbit. The process of aerocapture at Mars has been studied extensively in the past 10 years, and is likely to be adopted in some form in the near future. A limited amount of work has been done for the outer planets, and this is going on primarily at the NASA Ames Research Center.

Specifically, Ames has been concentrating on shaped, ablative entry type vehicles, with lift capability, and some closed loop control. An alternate method, using ballutes, an inflatable structure, has been looked at in a preliminary analysis at JPL to see if a simple, lighter, more passive method could be possible, which would operate at a higher altitude than a capsule.

in these calculations, made for Neptune aerocapture, the results look promising. An example is presented here assuming a spacecraft mass of 400 kg, and a ballute (spherical shaped) inflated to 36 m diameter. With a 7.6 deg entry angle at an altitude of 800 km (referenced above 1 atm), the ballute would dip to 600 km, and experience a maximum acceleration of 11 g's, and temperatures to 960° K. The aerocapture phase would last about 3 rein, and the lines to the ballute would be cut when cm-board accelerometers indicated that sufficient deceleration has been applied for orbit capture.

There are many open questions remaining in the use of ballutes for aerocapture. Some of these arc dynamic stability, stagnation temperatures, proper ballute shape, materials, mass estimate, and uncertainties or variations in the atmospheric density of Neptune.

Conclusions

Emerging technologies are changing the way we do deep space missions. instrument and spacecraft functions can be integrated and are complementary. Advances in electronics and materials can reduce mass substantially. These hold the promise that missions to the outer planets may be accessed in a time frame and for a cost similar to difficult Discovery missions within the orbit of Jupiter. Lowering spacecraft mass is an essential element in this pursuit.

How will this new technology develop, and what will space missions look like 10, 20, or 50 years from now? This will be driven by which technologies will progress more rapidly, and be more cost effective than another. The scenario envisioned here is that small, very capable spacecraft will be deployed, perhaps in large numbers, to far reaches of the solar system to gather data relevant to understanding solar system formation and evolution. This data will be transmitted, perhaps optically, to large receivers On or near Earth, and disseminated rapidly to researchers. Perhaps this process will become so commonplace, that no thought will be giver that one body is so much more distant thai another. At that point, the solar system wil belong to mankind.

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