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Technical Memorandum 33-454

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A Discussion

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Preface

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Contents

Abstract

This paper outlines some scientific objectives for imaging experiments on a fly-by of the outer planets: Jupiter, Saturn, Uranus, Neptune, and Pluto. Imaging experiments are proposed in atmospheres, satellites and rings, planetary figures, the surface of Pluto, and the asteroid belt. An attempt is made to demonstrate how the proposed experiments would close gaps in our current knowledge of the outer planets. Some functional requirements such as resolution and spectral bandwidth of the imaging system have been identified.

Scientific Objectives for Imaging Experiments at the Outer Planets

I. Introduction

This document outlines some scientific objectives for imaging experiments at the outer planets: Jupiter, Saturn, Uranus, Neptune, and Pluto. The information and opinions discussed here have been collected from the references.

The four outer planets called the major planets—Jupiter, Saturn, Uranus, and Neptune—are all large, low-density bodies with optically thick atmospheres. They differ greatly from the inner, or earth-like terrestrial, planets, and the missions to the outer planets are expected to help explain this difference. Pluto is small and of unknown density, and may lack an atmosphere. From our extremely limited knowledge of Pluto, this planet appears to be significantly different from the major planets. It has been suggested that Pluto is not properly a planet, but rather an escaped satellite of Neptune.

Although it is generally agreed that the five planets should not be given equal consideration in planning the outer planet missions, there is still some argument over which planets should have priority. One view is that Jupiter and Saturn should be emphasized because we know more about them and can, therefore, design a better experimental program. Also, the data rates will be highest at Jupiter and Saturn. The other view is that we should emphasize the outermost planets—Uranus, Neptune, and Pluto—because we know the least about them and even crude results would be a great improvement over our current knowledge. Also, it will be a long time—179 years—before we have similar opportunities to send missions to the farthest planets. Opinion seems to favor Jupiter and Saturn, at least for the mission with the earliest encounter dates. Pluto has been largely ignored.

II. Scientific Objectives

The outer planet missions are commonly thought of as exploratory flights. Current knowledge of these planets is not sufficient to permit planning for highly refined experiments. For this reason, flexibility should be emphasized in the design of the imaging system. In particular, it should be possible to command the imaging system during flight. Also, the system should be able to transmit far-encounter data early enough to permit evaluation before near encounter occurs.

Two additional arguments favor these capabilities:

(1) The duration of these flights is so great that significant ground-based or earth orbiter data could be acquired between launch and encounter, and such data may suggest new or modified imaging experiments. Space probe imaging can be justified only if the results are significantly better than earth-based data.

(2) There is a possibility that the spacecraft or the imaging system will be damaged by the radiation belts of Jupiter during near encounter. If this should occur, it is desirable that the far-encounter data not be lost, and that some measures can be taken to offset the damage.

The scientific objectives for the imaging experiment have been organized into six categories: atmospheres of the major planets, satellites and rings, planetary figures, Pluto, asteroids and the interplanetary medium, and support. These categories overlap each other somewhat. At the present time no proposals have been made to use the imaging system for exobiology studies at the outer planets.

A. Atmospheres of the Major Planets

There are three areas of interest pertinent to imaging studies of the major planet atmospheres:

(1) Structure of the molecular atmosphere, i.e., the material above the clouds.

(2) Structure of particulate matter, i.e., the clouds. This includes the bands and spots which are thought to be atmospheric features.

(3) Dynamics of the atmosphere.

In all three areas, our present knowledge is limited by earth-based resolution and photometric accuracy.

Statements of earth-based resolution must always be qualified, since this resolution depends on the optical resolving power, scene contrast, luminance, spectral bandpass, mode of detection (visual or photographic), and seeing conditions. Thus, a particular instrument will have one resolution for visual observation of stars and a somewhat lower resolution for photography of Jupiter's clouds. By comparison with the moon, the major planets have rather low contrast. Their great distance from the sun results in lower luminance, which in turn requires longer exposures and compounds the effect of turbulence in the earth atmosphere. The study of atmospheric dynamics requires a sequence of pictures taken over a period of days, and so the limiting factor is the resolution achievable on a day-to-day basis, not the resolution achieved during brief periods of excellent seeing. For this type of day-to-day photography, the best earth-based resolution is 2 to 3 arc-s. A resolution of 3 arc-s corresponds to 10,000 km at Jupiter, to 20,000 at Saturn, and to nearly the entire disk at Uranus and Neptune. A proposed *Orbiting Astronomical Observatory,* scheduled for operation in the mid-70s would permit consistent imaging with 0.1 arc-s resolution, or about 30 times better than the current, ground-based, day-to-day figure.

The best earth-based photometric accuracy is 0.5% relative, 5–10% absolute.[1] Typical figures are 2% relative and 10% absolute. Polarization measurements have been made with an accuracy of 0.1% relative.[1] The value of these data, however, is limited by the fact that the major planets can be seen only at small phase angles from the earth. The maximum phase angle is 12 deg at Jupiter, 6 deg at Saturn, 3 deg at Uranus, and essentially zero at Neptune. Also, earth-based photometry does not give localized data; the results are an average over most of the planetary disk.

1. Molecular atmosphere. The atmosphere above the clouds on the major planets consists mostly of molecular hydrogen and helium. Traces of ammonia and methane are present, and there is evidence of very small amounts of other molecules. The study of Rayleigh scattering gives information on optical depth, scale height, and hydrogen-to-helium ratio. For the data to be useful, the resolution must be on the order of one scale height—about 10 km on Jupiter. Scattering is strongest in the blue and near ultraviolet regions of the spectrum. At Uranus and Neptune, strong absorption in the red region is probably due to methane.

Objective

At each of the major planets obtain images of the limb with resolution of 10 km or better. Repeat at several wavelengths and several phase angles.

Note that if the limb is studied at large phase angles, the camera will be aimed in the general direction of the sun (small cone angle), and precautions will be needed to protect the camera.

[1]"Earth-Based Research on the Outer Planets During the Period 1970–1985," JPL internal document of August 15, 1969, R. L. Newburn, Jr., Editor.

The atmosphere of earth generates three types of nonthermal radiation: auroral, airglow, and cataclysmic radiation (lightning, meteor trails). The aurora is excited by energetic charged particles, and is concentrated near the magnetic poles. Both aurora and airglow are principally in the red and near-infrared regions. The atmospheres of the major planets are completely different from that of earth, so we cannot assume similar radiation on these planets. Of the major planets, only Jupiter shows evidence of a trapped particle belt.

Objective

Obtain pictures of the dark side of Jupiter to determine the extent of aurora and airglow.

2. ***Particulate matter.*** The clouds on the major planets make up the entire visible surface. Jupiter, Saturn, and Uranus have spots and colored bands that have been resolved from earth, and these are probably cloud features. Some questions about cloud structure apply to all the major planets:

What are the clouds made of?

What are the sizes and distribution of the clouds?

Are the clouds layered or convective?

Are there breaks in the uppermost cloud layer that expose the lower lying clouds?

Are the particles liquid or crystalline?

Do the various colored bands lie at different altitudes?

Jupiter shows the greatest variety of "surface" features. The clouds are probably ammonia cirrus[2]. There are cloud bands in several colors, and a variety of persistent spots. The most obvious feature is the great red spot, 40,000 × 13,000 km. Some outstanding questions remain to be answered:

What causes the great red spot?

What is it made of?

How deep is it? What is its altitude with respect to the cloud tops?

Why does it rotate with a variable period? Why is the average period not the same as that of the atmosphere?

What is the fine structure of the spot?

Saturn rarely shows spots, and those that do appear vanish again in a matter of hours or days. Although only 6 cloud belts have been named, as many as 21 have been reported. The clouds are probably ammonia.

Uranus appears featureless under normal seeing conditions, but under excellent conditions two belts are seen surrounding a bright central zone. These belts are inclined approximately 25 deg to the plane of the satellites of Uranus, which is also thought to be the equatorial plane. The bands are best seen in blue light. An overall greenish appearance indicates that the clouds are seen through a great depth of methane. Recent studies suggest that the banded structure could result from moderate temperature inhomogeneities in hydrogen rather than from methane.

From earth, Neptune appears featureless except for rare reports of spots. As with Uranus, there is a green color probably due to absorption in methane.

Objectives

At each of the major planets obtain a series of pictures of the clouds, belts, and spots, beginning with earth-based resolution and extending to a resolution of 10 km or better to determine both large- and small-scale structure and distribution.

Image the clouds, the bands, and particularly the red spot away from the subsolar point to determine vertical structure. Use colored filters to distinguish the various bands—red and blue filters a minimum. Resolution of 10 km required.

Photograph the clouds, bands, and red spot at many phase angles to determine the phase function. Do this at several wavelengths.

Image the full disk of Uranus in blue light to confirm the 25-deg inclination of the bands.

Photograph the shadows of any satellites that cross the field of view to determine vertical structure in the clouds. Resolution of 10 km needed.

[2]Melbourne, W. G., et al., *Constants and Related Information for Astrodynamic Calculations*, Technical Report 32-1306. Jet Propulsion Laboratory, Pasadena, Calif., July 15, 1968.

There is a launch window of approximately 20 days for the outer planet missions, and there is some flexibility in carrying out the required midcourse corrections of the spacecraft trajectory. This freedom can be used to select the location of the red spot or the Galilean satellites at the time of encounter with Jupiter.

Light scattered from particulate matter in the atmosphere is partially polarized in a manner characteristic of the specific particles. There is now some question about the sensitivity required for making reliable polarization measurements.

Objective

At each planet photograph the disk through polarizing filters to study the particle content of the atmosphere.

No statements of the required photometric or polarimetric accuracy have been found. The previously stated accuracies for the best ground-based experiments are quite high. However, it is likely that experimenters would be willing to sacrifice some accuracy in exchange for more localized data and a wider range of phase angles.

3. ***Dynamics.*** The dynamics of the atmosphere is related to the way in which heat and angular momentum are transferred among the various layers of the atmosphere and the planet. The movement of the atmosphere is partially coherent and partially turbulent. The coherent aspect of the motion is the basis for a definition of rotation period.

The period of rotation of the major planets is not a well-defined concept. It could be taken as any one of the following:

(1) Period of rotation of the solid surface of the planet. This definition is of little use in planning imaging experiments at the outer planets. All the major planets have cloud layers that obscure the solid surface at visible wavelengths. In fact, models of Jupiter indicate that this planet may not even have a solid surface.

(2) Period of rotation of the atmosphere. This definition of the period suffers from the fact that planetary atmospheres are in differential rotation, making the choice of a period somewhat arbitrary. Periods of the atmosphere can be measured by imaging some persistent feature in the atmosphere or by using doppler spectroscopy.

(3) Period of rotation of the magnetic field. This is observed by measuring the period of nonthermal radiation sources associated with the planet. These radio frequency emissions are synchrotron radiation from charged particles trapped in the magnetic field of the planet. At present, only Jupiter among the outer planets has shown this nonthermal radiation.

(4) Period of rotation of localized radio frequency sources. Decameter radiation is emitted from localized sources on Jupiter, and these sources rotate with a period different from that of the synchrotron radiation.

The imaging experiment at the major planets will be concerned with the rotation of the atmosphere (definition 2).

The atmosphere of Jupiter rotates in two fairly distinct systems. System I is a belt surrounding the equator and extending to ±10 deg. System II comprises the remainder of the visible surface. For a means of reference, exact periods have been defined for these systems; but the actual rotation at a given time and latitude may depart from the defined period by several seconds.

System	Period
I	$9^h50^m30\overset{s}{.}003$
II	$9^h55^m40\overset{s}{.}63$

Earth-based photography lacks the resolution needed to reveal the details of the slip zone between the two systems.

The atmosphere of Saturn is in differential rotation, the period varying smoothly from 10 h 2 min ± 4 min at the equator to a period 11% longer at 57 deg. Saturn rarely shows persistent spots large enough to be seen from earth, so these data are from doppler measurements. When spots do appear, their apparent periods are longer than the doppler periods (about 10 h 14 min at the equator). Spots may be more numerous at the larger scale available near the planet.

The periods of Uranus (10.8 h) and Neptune (15.8 h) have been determined spectroscopically to within ±6%.

Atmospheric features suitable for period determination have not been resolved for either planet.

Very little is known about the small-scale motion of the major planet atmospheres. The atmospheric spots move relative to each other, at rates that are often different from that of the rest of the atmosphere. Also, there is evidence that Jupiter and, perhaps, Saturn have internal sources of heat. If these sources are at all localized, this fact may be revealed by the movement of the atmosphere.

Objectives

At each of the major planets, obtain a sequence of full disk pictures over a span of weeks to determine the period(s) of the atmosphere to better than 1%. This will require resolving persistent features with dimensions on the order of 1000 km or less.

At each planet, photograph selected regions with high spatial and temporal resolution to study the small scale dynamics of the atmosphere. A spatial resolution of 10 km is desirable, but 100 km would provide some useful information. The pictures should be repeated as often as every 15 min. A wide field of view is needed so that the limb, or terminator, can be included as a reference line. These pictures should concentrate on areas of turbulence. At Jupiter, they should record the movement of small spots relative to the great red spot.

At Jupiter, photograph the slip zone between Systems I and II to determine the small-scale dynamics of this region. Resolution should be 10 to 100 km, and a wide field of view is needed. These pictures should be repeated as often as every 15 min. These pictures, together with those called for in the two preceding objectives, may be sufficient for a comparative study of differential atmospheric rotation on the four major planets.

At Uranus, obtain a series of pictures in the region of the bands. The possible inclination of these bands to the plane of the equator justifies this special attention. Resolution should be 10 to 100 km.

B. Satellites and Rings

Jupiter and Saturn have the greatest number of satellites. Of Jupiter's twelve satellites, five (I–V) are regular; the four largest (I–IV), named for their discoverer, are called the Galilean satellites. Saturn has ten known satellites. The sizes of the three largest of these are shown here, together with Jupiter's regular satellites:

Satellites		Diameter, km
Jupiter		
J-V	(Almalthea)	100
J-I	(Io)	3340
J-II	(Europa)	2920
J-III	(Ganymede)	5100
J-IV	(Callisto)	4720
Saturn		
Rhea		1300
Titan		4800
Iapetus		1300

Uranus has five satellites, of which very little is known. The four largest have diameters of about 1000 km. Neptune has two satellites – Triton, with a diameter of ~4000 km, and Nereid, with a diameter of ~200 km. Pluto has no known satellites. Some unanswered questions about the satellites of the outer planets are of interest:

What are the satellite diameters? These are inaccurately known, especially at Uranus and Neptune.

How much do the smaller satellites depart from a spherical figure?

What is the small-scale appearance of the satellite surfaces? Are there impact features?

What material makes up the surface of the satellites? Is snow present?

Do satellites other than Titan have atmospheres? What is the nature of these atmospheres?

Is there an undiscovered satellite of Saturn just outside the rings?

What are the periods of rotation? Is the rotation synchronous?

What are the satellite densities?

Why is one hemisphere of Iapetus more than six times as bright as the other?

Why is Io brighter than normally for 15 min following a solar eclipse by the primary? Is there an atmosphere on Io that freezes during eclipse and then vaporizes in the 15 min after the satellite emerges into sunlight?

Objectives

Obtain high resolution (10 km) images of the satellite surfaces to reveal surface features.

Obtain a series of full-disk images of the satellites to determine diameter, shape, and period of rotation.

Obtain images at several phase angles to determine geometrical albedo and phase function. These measurements are particularly valuable for the two hemispheres of Iapetus and for Io during the period following its solar eclipse.

Obtain ultraviolet images of the satellite limbs to determine the existence of atmospheres. Resolution of 10 km may give information on the constituents of any atmospheres found. These images are particularly valuable at Titan, Iapetus, and Io.

The significance of the satellite pictures is enhanced by the fact that we cannot see the solid surface of their primaries.

Current models of the rings of Saturn put the thickness at tens of centimeters and the particle size at microns. Alternate models suggest larger particles and a thickness of 10 km. In any case, these dimensions are too small to check by direct imaging, but they can be studied photometrically.

Objectives

Obtain images of the rings at various phase angles, to determine geometric albedo and phase function.

Obtain images of the divisions between rings with a resolution of 100 km, to determine the density profile of the gaps.

Attempt to photograph bright stars as seen through the rings, to be compared with images of the same stars when not attenuated by the rings.

C. Planetary Figures

The figure of a planet is specified by giving the equatorial diameter (or radius) and the flattening. The flattening is measured either geometrically—by optical imaging of the planet, or dynamically—by observing the effect of the equatorial bulge on the satellites of the planet. The geometrical flattening is defined by

$$f = \frac{a_e - b}{a_e}$$

where a_e is the equatorial radius, and b is the polar radius. If both radii can be recorded in the same image, the ratio f can usually be determined with greater accuracy than the absolute quantities a_e and b.

For astronomical calculations (such as density), the planetary diameters should be known to better than 1%.[2] The diameters of Jupiter and Saturn are known to this accuracy; those of Uranus, Neptune, and Pluto are not. The diameters and probable errors for this second group of planets are given as follows:

Planet	Diameter, km	Uncertainty	Source[1]
Uranus	47,000	10%	pp. 52, 56
Neptune	50,000	5%	pp. 60, 63
Pluto	5,860	50%	pp. 66–67

Objective

Obtain full-disk images of Uranus, Neptune, and Pluto to determine the equatorial diameter to better than 1% accuracy.

The geometrical flattening should also be known to better than 1%.[3] Again, the values for Jupiter and Saturn are known to this accuracy; those for Uranus, Neptune, and Pluto are not. In fact, there is no data at all for Neptune and Pluto, and the results of various studies of Uranus differ by 50%.[3] From the definition of the geometrical flattening, it appears that the best way to measure f from a flyby is to image the entire disk while the planet is at full phase and the spacecraft is in the equatorial plane.

[3]Newburn, R. L., Jr., *A Brief Survey of the Major Planets: Jupiter, Saturn, Uranus, and Neptune,* Technical Memorandum 33-424, Jet Propulsion Laboratory, Pasadena, Calif., April 1, 1969.

Objective

Obtain full-disk images of Uranus, Neptune, and Pluto from near the equatorial plane of each planet to determine the geometrical flattening to better than 1% accuracy.

In the case of Uranus, this objective cannot be met because of the large obliquity (98 deg) of the planet. In 1966, the planetary axis was normal to a radius vector from the sun; in 1988, the axis will be directed along this vector. The outer planet flights will encounter Uranus when it is nearly in this second orientation. Therefore, the only full-phase view of Uranus will be nearly a pole-on view.

D. Pluto

The scientific objectives for imaging at Pluto are discussed separately because this planet is very unlike the major planets. Pluto is small, and because of its low mass and temperature probably has a very thin atmosphere at best. No features of Pluto have been resolved from earth. The period of Pluto ($\sim$6 days) has been measured photometrically, but there is great uncertainty in the result. Earth-based measurements of diameter and mass indicate a very high density, but the uncertainty in the diameter makes this conclusion tentative.

Objectives

Obtain a series of full-disk pictures of Pluto beginning with earth-based resolution (the entire disk) and continuing to a resolution of about 10 km to determine size, shape, and rotation period.

Photograph the limb in the ultraviolet to detect and perhaps identify any atmosphere present. Resolution of 10 km or better needed.

Obtain high resolution pictures near the terminator to determine the small-scale appearance of the surface. Wide coverage is needed to determine the size and distribution of any impact features, mountains, and other topographic features. Resolution of 10 km is desirable.

Photograph the surface at several phase angles and wavelengths to determine the photometric functions.

The photographs of Pluto can be compared with those of the terrestrial planets, the moon, and the satellites of the major planets (especially Neptune) to help determine the nature and history of Pluto.

E. Asteroids and the Interplanetary Medium

Of the many thousands of asteroids, only about 20 have diameters in excess of 100 km. The orbits of the larger asteroids are known, but no calculations have been made to determine how these orbits will intersect the trajectories of the proposed missions. If a lucky encounter should be made, it would be of great interest to photograph an asteroid. The variations in brightness shown by many of the bodies are probably due to their elongated shapes. Current projections for the outer planet spacecraft indicate that image data can be transmitted in real-time at the asteroid belt, thereby making a search for asteroids more practical.

Objective

Attempt to photograph an asteroid while the spacecraft is passing the asteroid belt.

If the imaging system is capable of long exposure times, it may be possible to photograph the zodiacal light while the spacecraft is in the cruise mode between planets.

Objective

Attempt to photograph the zodiacal light from new locations in the solar system.

F. Support

There are two areas in which the imaging system could be used in a support role: guidance, and boresight of other scientific instruments. In the guidance program it would be necessary to image the satellites of the major planets against an appropriate background of stars during far encounter. The dynamic range of the camera must be sufficient to accommodate this brightness range without diffusion of the satellite images from overexposure. The guidance function also requires very exacting calibration of the imaging system geometry. This could be done by imaging the star field during the cruise mode.

An effort will be made to obtain localized data with the other scientific instruments, particularly an infrared radiometer (if one is flown). This data will be more useful if it can be correlated with images of the same area. Of particular interest are thermal maps of Jupiter and Saturn. Evidence indicates that the lighter-colored cloud bands radiate more heat than the dark bands, and this will be checked. The energy flux near the red spot of Jupiter should also be studied. The resolution called for in other parts of this report should be adequate for the boresight function of the imaging system.

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