PLUTO EXPRESS: REPORT OF THE SCIENCE DEFINITION TEAM

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1. Executive Summary

The Pluto Express mission is designed to provide the first reconnaissance of the Solar System's most distant planet, Pluto, and its moon Charon. To be viable in the current environment of tight financial limitations, the mission will be the first to employ a new philosophy of integrated spacecraft, instrument and mission operations design (“sciencecraft”), which necessitates a tight collaboration between selected instrument builders and spacecraft designers.

Tremendous progress in understanding Pluto and Charon enabled a well-focussed set of questions to be developed which can be addressed by a first spacecraft reconnaissance of the system. Fundamental questions regarding the physical and chemical processes in protoplanetary disks and their relationship with the surrounding nascent molecular cloud will be addressed through study of Pluto and Charon, as well as investigation of the environment of the outer Solar System during its early history from analysis of the cratering and tectonic records of these bodies. The physics of the unique evolution of Pluto's atmosphere as the planet moves away from the sun will also be a focus of study on this mission.

The baseline mission will involve two identical sciencecraft on flyby trajectories of the Pluto/Charon system. The spacecraft will carry an integrated array of scientific sensors which will conduct measurements capable of satifying at least the Category 1a science objectives regarding Pluto's atmosphere and surface, and Charon's surface, developed by the Outer Planets Science Working Group and detailed herein. Radio science provides an essential complement to fulfill these goals, and will be incorporated as part of the sciencecraft subsystems.Science investigation teams will be competitively selected and expected to work closely with spacecraft designers to produce an integrated sciencecraft within the stringent cost, mass and power constraints of the mission.

The recent discovery of dozens of objects, from comet-sized up to hundreds of kilometers, orbiting in the predicted Kuiper Belt region just beyond the planets, has raised the exciting possibility of an extended mission to fly close to one or two such bodies. If implemented, this extended mission would allow comparison of the properties of Pluto and Charon with the smaller bodies from which they (and the larger outer planets) were likely assembled.

As befits an exciting mission to the outer reaches of the Solar System, substantial interest exists from two international partners. The German space agency, DARA, has played a strong role in developing two possible collaborative scenarios: If the spacecraft are launched on trajectories which allow a Jupiter gravity assist, DARA could provide a detachable probe spacecraft to explore Jupiter's moon Io and its environment. A second possibility would be construction of a particles and yields experiment package to be used to investigate the interaction of Pluto and its atmosphere with the solar wind. The Russian space agency, RSA, is interested in possibly supplying a Drop Zond to investigate Pluto's atmosphere in situ prior to impacting on Pluto's surface.

Mission studies underway now could lead to a launch early in the next decade of the Pluto Express mission, allowing the primary targets to be reached roughly a decade after.

2. Rationale for Mission

Six years after Voyager 2 flew past Neptune, Pluto remains the only planet in our Solar System which has not been visited by spacecraft. Perched on the outer edge of the classical realm of the planets, and just within the Kuiper belt of primitive material remaining from the Solar System's formation, Pluto and its moon Charon hold chemical clues to the conditions at the interface between the protoplanetary disk itself and the precursor molecular cloud. Their small size makes it likely that these clues are at least partially preserved in the molecular composition of their ices, unlike the material in the vastly more massive giant planets. However, Pluto's large size (and high albedo) relative to other icy bodies has made it accessible to study from Earth in sufficient detail to know that it possesses a surface containing frosts of very volatile species which also occur in comets and which are confirmed or suspected to be present in molecular clouds. The density of Pluto is consistent with an internal mixture of rock and ice which is close to the value predicted for primitive Solar System material.

Pluto is known to have an atmosphere, and one whose energy balance is unique in the Solar System. The atmosphere is almost certainly dynamic and transient, and will decrease in mass or collapse as Pluto continues to retreat from its 1989 closest approach to the sun. Pluto's small size means the atmosphere must be escaping the planet at a rapid rate, making it intermediate in stability between those of comets and those of larger planets.

What we know of Pluto is enough to make this smallest planet intriguing, but much remains unknown. We do not know how the ices are distributed across Pluto's surface, nor how geology has shaped its surface. Many trace species beyond those detected on the surface undoubtedly exist. The nature of the dark material on Pluto is unknown, in particular whether it is organic material processed by cosmic rays or sunlight, or simply silicates. We only inferentially understand the structure of the atmosphere, and available models only hint at its composition and dynamics. We do not know how the atmosphere will respond to the decrease of insolation as Pluto recedes from the Sun. We suspect that Pluto does not have a significant intrinsic magnetic field, but even a small magnetization would suffice to stand off the solar wind. The inferred atmospheric escape rates suggest a comet-like interaction with the solar wind if such a field is not present - an interaction possibly unique in the Solar System.

We know far less about Charon, including its surface appearance, compositional relationship to Pluto, and origin. The surfaces of both Pluto and Charon might show the scars of their early history, in terms of craters and tectonics induced by tides or impacts, but we cannot tell without very high resolution imagery. The close correspondence in size of Pluto and Charon (closer than that of any other planet-moon system) is also a mystery.

Many of the questions posed about Pluto and Charon (discussed in detail below) can only be addressed by a spacecraft mission which brings advanced instruments close to the two bodies. The level of knowledge of all other planets and their moons increased enormously through visits by spacecraft, and it is well-understood, particularly after Voyager and Magellan, how essential spacecraft exploration is to understanding the nature of the Solar System.

The recent discovery of many objects beyond Neptune and Pluto in orbits corresponding to the predicted Kuiper Belt has opened another exciting dimension for this mission of exploration. Kuiper Belt objects are likely to be remnants of Solar System formation, holding clues to the birth of the planets in stable and well-defined orbits, which have never taken them close to the sun. A possible extension beyond Pluto to visit one or more of these objects would be an extraordinary complement to a Pluto flyby, such that the whole suite of outermost primitive bodies from comet-sized objects to planets is reconnoitered.

Beyond the scientific value of a Pluto mission, the technological challenge ts well NASA's intention to develop new, low-cost spacecraft employing advanced technologies. These *sciencecraft* spacecraft are essential if the nation is to continue its vigorous program of scientific exploration of the cosmos under the severe funding limitations which NASA faces in the forseeable future. A program to develop and implement technologies to achieve these goals, *New Millenium*, is also beginning. A mission to fly past Pluto and Charon and obtain and comprehensive set of measurements, a “Pluto

Express", is well-matched to exercising the capabilities of the sciencecraft philosophy and potentially to take advantage of the New Millenium program. If successfully executed, the mission will assure the United States of continued access to the deep outer Solar System during difficult financial times.

The Pluto-Charon mission responds to political and emotional imperatives regarding space exploration. Pluto as a place sparks the imagination of the public, and the concept of a mission to the Solar System's most distant planetary outpost has demonstrated high public appeal. Interest on the part of international partners in participating in this venture, in particular the German Space Agency DARA and the Russian Space Agency, has opened the possibility of doing additional science at Pluto and possibly other targets during the mission.

3. History of Advisory Group Considerations and Recommendations

Missions to Pluto were discussed seriously during planning for the Voyager missions of the 1980's. The option of sending one Voyager on to Uranus and Neptune after Saturn was exercised with Voyager 2. Voyager 1 could have been directed toward a Pluto flyby, but only at the cost of sacrificing a close encounter with Titan, a Saturnian moon larger than Mercury and with a thick nitrogen atmosphere. The Voyager 2 results at Titan helped galvanize support in the United States and Europe for a follow-on detailed study of the Saturn system, Cassini Huygens, and NASA's decision on trajectories was fully appropriate.

Advisory group recommendations of the mid-1980's regarding a Pluto mission were generally positive, but must be read in the context of the great dearth of information available about the planet and its moon then relative to today. The 1986 COMPLEX strategy for the exploration of the outer planets states

After the Voyager encounter of Neptune, Pluto will be the only unvisited planet in the Solar System, and will continue to be an important target for Earth-orbital and Earth-based studies. As a goal for the long-term, a Pluto flyby or orbiter is clearly of great interest.

The first serious incorporation of a Pluto mission into NASA's strategic planning came with the 1991 Woods Hole activity to develop a five-year plan for missions spanning the full range of space science disciplies. NASA's Solar System Exploration Division (SSED), under the recommendations of its Solar System Exploration Subcommittee (SSES) proposed dual Neptune- orbiter and Pluto flyby missions, with a scope and cost comparable to that of Cassini (Solar System Exploration Strategic Plan, 1991). Budgetary constraints forced the Division to choose between the Neptune orbiter and Pluto flyby mission, and with the help of the Outer Planets Science Working Group (OPSWG) and SSES selected the latter.

The mission under consideration then was descoped to the so-called *Pluto Fast Flyby*, with an imposed cost cap of $ 400 million (FY92) through launch plus 30 days. In 1992 OPSWG formulated a prioritized list of science objectives, and derived measurement objectives and a strawman payload which could accomplish the key objectives of a Pluto-Charon reconnaissance flyby.

The SSES recommended incorporation of the Pluto Fast Flyby mission for an FY 2000 new start in the SSED plan. The SSES stated, in its 1994 Strategic Planning document:

The motivation for sending a mission to reconnoiter the Pluto-Charon system is severalfold. In part, it is based on the intense scientific interest and the potential for fundamental discoveries...Other motivations for Pluto reconnaissance include its wide public appeal, strong technology focus, and particularly cost effective nature, compared to most other outer Solar System missions.

In October, 1994, NASA Administrator Goldin decided that the cost of the Pluto Fast Flyby mission could not be borne within the projected NASA budget over the next decade, and initiated study of the current Pluto Express mission within the context of Sciencecraft integrated spacecraft philosophies and the possible use of New Millenium technologies. Given recent Administration and Congressional reductions in the NASA budget through the year 2000, it is now clear that, if a mission to Pluto satisfying the highest priority science objectives is to y, it will be in the context of the present Pluto Express mission. For further details of the history of the mission the reader is referred to Stern (1993).

A first reconnaissance of Pluto has a substantial history in the planetary program. The current Pluto Express mission represents a well-focussed plan to address the highest priority science in a fiscal environment in which all science missions proposed for the next decade have been forced into substantial descoping and reconfiguration exercises.

The pace of significant discoveries regarding Pluto and other objects in the outer Solar System has accelerated. Some significant science breakthroughs for the Pluto system, and their dates, are listed below.

- 1930: Pluto discovered, orbit determined;
- 1955: 6.4 day rotation period determined;
- 1965: 3:2 orbit resonance with Neptune discovered;
- 1973: Pluto's extreme obliquity discovered;
- 1976: Discovery of CH_4 ice on Pluto;
- 1978: Discovery of Charon, mass of the combined system determined;
- 1985: Onset of Pluto-Charon mutual events;
- 1986: First reliable radii for Pluto and Charon;
- 1986: Determination of Separate albedos and colors for Pluto & Charon;
- 1987: Discovery of H_2O ice on Charon;
- 1987: IRAS yields thermal IR Data;
- 1988: Discovery that Pluto's orbit is chaotic;
- 1988: Stellar occultation reveals Pluto's atmosphere;
- 1988: Eclipse evidence for polar caps;
- 1989 Inference of thermal structure and molecules heavier than methane in Pluto's atmosphere;
- 1992: Discovery of N_2 and CO ice on Pluto;
- 1992: Discovery of numerous trans-Neptunian objects;
- 1994: Discovery of CH_4 in Pluto's atmosphere;
- 1995: Hubble Space Telescope images reveal polar caps on Pluto;
- 1995: Tentative detection of comet-sized bodies in the trans-Neptunian region.

In the following section, we review what is known about Pluto, Charon and related objects in the outer Solar System as a foundation for the science objectives of a first spacecraft reconnaissance mission.

4. Current Understanding and Outstanding Questions

4.1. INTRODUCTION

Fifteen years ago we did not know enough about Pluto and Charon to merit a substantial review article in a refereed journal. Today, the situation is different, with a major book on these objects in preparation (Stern and Tholen, 1996) and substantial commitment of ground-based and orbital facilities for continuing observations. The following summary of our knowledge is intended to give a flavor for the intellectual foundation around which a first reconnaissance mission is being designed. It must be emphasized that in each of the disciplines covered, significant questions exist which can be addressed best (or only) by a close flyby mission. The table below summarizes the basic parameters of the Pluto Charon system.

TABLE 1. Basic parameters of the Pluto system

Parameter	Pluto	Charon
Rotation Period	6.3872 days	6.3872 days
Radius	1164-1187	590-630 km
Perihelion V0	13.6 mag	15.5 mag
B Geometric Albedo	0.55	0.32
V-I Color	0.93 mag	0.83 mag
Known Surface Ices	CH_4, N_2, CO	H_2O
Atmosphere	Confirmed	Doubtful

cf., Null, et al. 1993.

4.2. ORBITAL PARAMETERS

Pluto and Charon lie at a mean distance from the sun of 39.4 AU; their heliocentric orbit was determined with reasonable accuracy within the first few years following Pluto's discovery in 1930. However, with prediscovery observations extending back only as far as 1915, observations presently span only about one-third of the 248-year orbital period. As a result, the mean motion is still not known as well as for the other planets, which limits the accuracy with which long-term numerical integrations can be performed. The orbital integrations that have been done show Pluto to be in a 2:3 resonance with Neptune, which prevents close approaches to that planet. The resonance has not been seen to break over the length of the integrations, which now extend to the age of the solar system.

Knowledge of the orbit of Charon around Pluto, which is essential to understanding the dynamics of the system, densities of the bodies, and even the radius of Pluto has been undergoing constant improvement since the satellite's discovery in 1978. The combination of the semimajor axis and orbital period provides the mass of the system, which when coupled with radii for the two objects, yields the mean density of the system, the significance of which is described in section 4.3.2. The orbital period is the easier of the two to measure. Accurate timings of mutual eclipse and occultation phenomena between Pluto and Charon during the orbit plane crossing of 1984-1990 yielded an orbital period of 6.38722 days. The semi- major axis is far more difficult to determine, requiring direct imaging of the system, which at maximum separation spans a mere 0.9 arcsec. Ground- based efforts to measure the semimajor axis are limited by atmospheric seeing effects, giving error bars in the 100 km range. Space-based observations with the Hubble Space Telescope (HST) are capable of higher spatial resolution now that the optics are repaired (Tholen and Buie, 1995). While Charon's orbit lies roughly in Pluto's equatorial plane, significant discrepancies remain in various determinations of the precise orbital inclination, presumably due to systematic errors in the calibration of the position angle for the major axis of the projected ellipse.

A recent development is the detection of a significant non-zero eccentricity in the motion of the center of light of Charon around the center of light of Pluto (Tholen and Buie, 1995). The two centers of light depend on the assumed surface albedo distribution, and although the eccentricity can be reduced by incorporating current albedo maps of the system, a significant non-zero value remains. Precise determination of the eccentricity can be achieved by a spacecraft flyby, either by direct imaging of the orbital motion of Charon about Pluto, or improvement in our knowledge of the surface albedo distribution (which allows more precise Earth-based tracking of the centroids of each object).

4.3. BULK PARAMETERS

4.3.1. *Radii*

Four different techniques have been used to measure the radii of Pluto and Charon: speckle interferometric imaging, stellar occultations, mutual events, and direct imaging with the HST Faint Object Camera. The speckle determinations suffer from assumptions about surface albedo distribution and limb darkening, are quite discrepant, and have the largest error bars of the four techniques. Because they are no longer competitive with the more recent measurements, we do not discuss them further.

Only two stellar occultations have been successfully observed, one for each body. The Charon occultation was seen from only a single site, hence the chord length provides only a lower limit of 601 km to the radius of Charon. The Pluto stellar occultation was observed from several sites, but the discovery of an atmosphere around Pluto makes radius determinations dependent on models of the atmospheric temperature profile (Elliot et al., 1989; Stansberry et al., 1994). Model radii for Pluto are in the 1180 to 1200 km range, with smaller values accommodated by assuming, for example, the presence of a troposphere.

The mutual event radius determinations rely on an accurate value for the semimajor axis of Charon's orbit to provide the physical scale. Although theoretically capable of the highest accuracy of the four techniques mentioned, some slight model dependencies remain, particularly due to the assumed limb darkening (Buie et al., 1992). The results place the radius of Pluto in the 1150 to 1160 km range, while Charon falls in the 590 to 630 km range (Albrecht et al., 1994).

Direct images by HST using the Faint Object Camera suffer from lack of knowledge about the limb darkening. Furthermore, Charon is barely resolved. In spite of these limitations, the results are comparable to those obtained from the occultation and mutual event modeling techniques (Buie et al., 1995).

A spacecraft flyby can provide accurate radii that are not limited by the limb darkening assumptions that afflict the techniques used to date, resulting in significant improvements in the radii of Pluto and Charon and hence in the derived densities.

4.3.2. *Rotation*

Rotational information for Pluto and Charon is based on accurate photometric observations extending over four decades. Because the light from the system is dominated by the light from Pluto, this information mainly tells us about the rotation rate and large obliquity (120) of Pluto. Only recently have resolved observations from HST provided an indication of Charon's rotational properties. Dynamical arguments suggest that Pluto and Charon are tidally locked, and the available data do not contradict these arguments.

4.3.3. *Densities*

The limiting factor in our knowledge of the system mean density lies with the radii, which are discussed above. Of more interest, however, are the individual densities, which rely on knowing the mass ratio of the two bodies. Two attempts to measure this mass ratio in 1991 (HST) and 1992 (ground-based) yielded completely different results (Null et al., 1993; Young et al., 1994). Both sets of observations were repeated in 1993 (HST) and 1995 (ground-based), but it is too early to say whether the discrepancy will be resolved. At this point, all that can be said is that the system mean density is approximately 2.05 grams per cubic centimeter, with the individual density of Pluto being near this value, and Charon being either as dense as, or somewhat less dense than, Pluto.

4.4. INTERNAL STRUCTURE

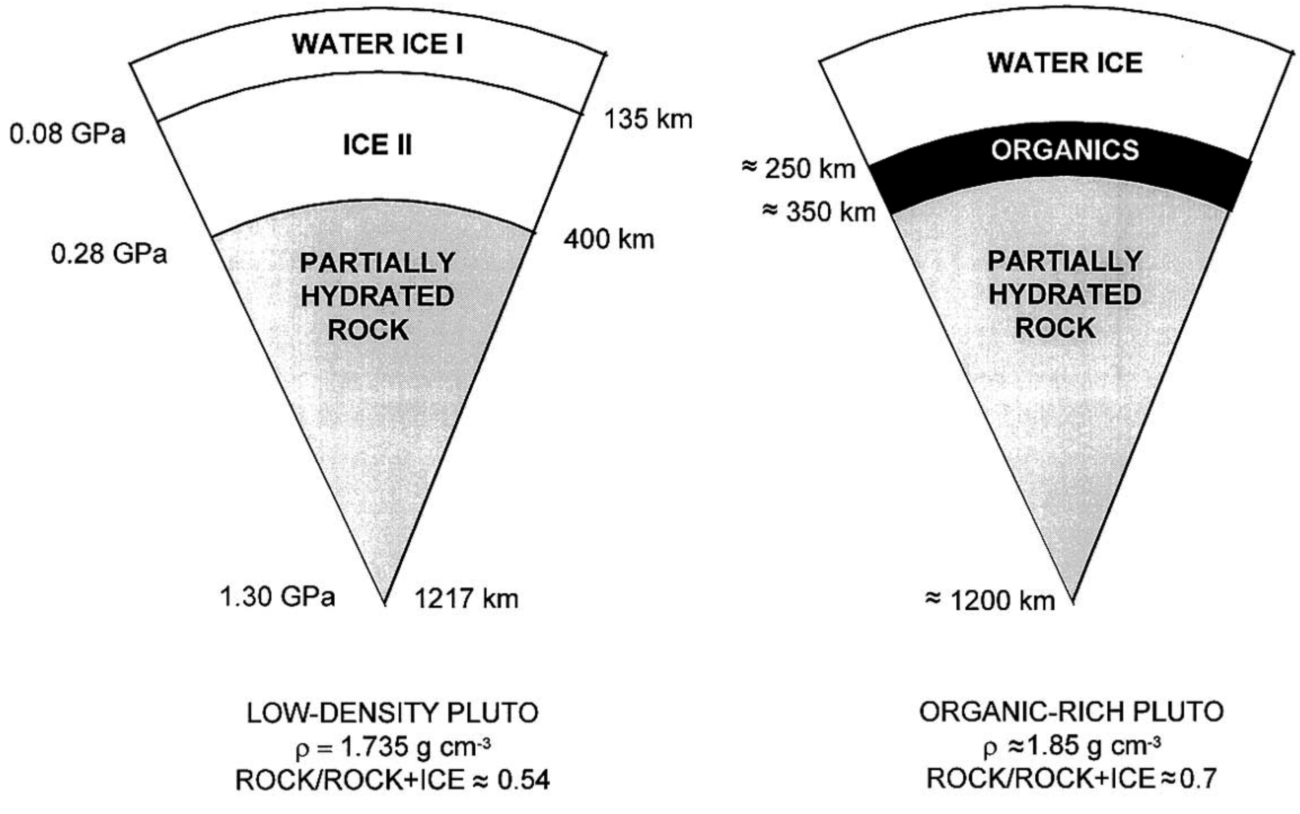


Figure 1. Two models of the interior of Pluto, shown in cross section; pressure in gigapascals shown on the left. Ice I and Ice II are low and high pressure phases of water ice, respectively. Figure from McKinnon et al. (1995).

Given the density, radius, and information on the rotational state of Pluto and Charon, along with basic data on the rheology of ices and rock, internal structure models of Pluto and Charon can be constructed. Because of the high cosmochemical abundances of water ice and silicates, these are assumed to be the predominant constituents. Figure 1 shows a resulting model for Pluto, from McKinnon et al. (1995). Models for the formation of Charon by impact of a large body into Pluto imply substantial heating of Pluto's interior, leading to softening of the ice and separation of the rock to form a core (this might well happen in any event as radioactive elements in the rock heat the interior and soften the ice). The same exercise can be performed for Charon but the current uncertainty in its density prohibits definitive results.

Quantitative interior models permit an estimate of the mass fraction of rock, relative to ice, which is present in Pluto's interior. This can be compared to the fraction expected in a primordial mixture of rock and ice from which outer solar bodies were accreted (McKinnon and Mueller, 1988; Stern, 1989; Simonelli et al., 1989). As described in Stansberry et al. (1994), the current uncertainty in Pluto's radius prohibits a definitive result, but it appears that Pluto has a somewhat higher rock-to-ice ratio than predicted for primitive material. Loss of water early in its history, perhaps as a result of a Charon-forming impact, is a plausible explanation for the slightly rock-rich nature of Pluto (e.g., McKinnon, 1989). However, a more definitive determination of the radius is required before the amount of water loss can be estimated.

4.5. ALBEDO MARKINGS

Next to Iapetus, Pluto has the largest global-scale surface contrast in the Solar System. Indeed, Pluto's rotational lightcurve shows brightness variations of about 0.35 mag (i.e., 30 percent disk-integrated brightness viewed equatorially). which provides the primary evidence for large-scale albedo variations over the surface of Pluto. The locations of those markings are further constrained by the way in which the lightcurve amplitude has increased over the years since precise photometry began in the mid 1950s. Models based on the assumption that the markings could be approximated by circular spots were developed by Marcialis (1983), Buie and Tholen (1989), Young and Binzel (1993), and Reinsch et al. (1994).

Once Charon started occulting Pluto during the mutual event season of the 1980s, it became possible to map the locations of albedo markings with somewhat higher spatial resolution, but over only Pluto's Charon-facing hemisphere, due to the tidal lock between the two bodies. Models have been computed by Buie et al. (1992) and Young and Binzel (1993). They both show a bright south polar cap and a darker equatorial region.

Direct imaging with the repaired HST has provided a more definitive means of mapping out the locations of albedo features on Pluto, and although the spatial resolution is somewhat lower than for the maps based on mutual event observations, global coverage is possible. The first such observations show polar caps and large equatorial spots (Stern, in preparation).

Charon is only barely resolved by HST, so once again we must rely on rotational lightcurve information to constrain the global albedo variation, given that the mutual event data also map out only one hemisphere of Charon. The lightcurve of Charon, as measured from HST, shows less than 0.1 mag variation, indicating a much more uniform surface (Buie et al., 1995).

As a function of wavelength, the albedo of Charon appears constant (i.e., grey) throughout the visible part of the spectrum, whereas Pluto's albedo increases with wavelength until the strong methane absorption features are encountered at near infrared wavelengths. At 0.44 (m, Charon's reflectivity is about 40 percent, while Pluto's surface varies in the 40 to 60 percent range over spatial scales comparable to the size of Charon. The contrast is presumably much higher over smaller scales.

4.6. SURFACE COMPOSITION AND PHYSICAL STATE

Pluto's surface is covered with materials of diverse chemical composition and reflectivity. The discovery many years ago of the planet's changing brightness during its rotation demonstrated there is a non-uniform distribution of dark and bright surface materials on its surface, and at the same time permitted the determination of the diurnal period of 6.3872 days.

The bright material on Pluto appears to consist primarily of solid nitrogen, with various other volatile molecules present as secondary frosts or mixed with nitrogen as a contaminant (Owen et al., 1993) Spectroscopic observations with Earth-based telescopes show that methane included in the N_2 constitutes approximately 1 percent (by mass) while carbon monoxide in the mixture contributes somewhat less than 1 percent of the large expanses of the solid N_2.

Molecular nitrogen ice tends to form large crystals in the laboratory, and on Pluto might anneal and sinter into large semi-transparent expanses many meters in dimension. The detailed properties of the N_2-covered regions of Pluto's surface are not known, but the spectroscopic evidence suggests variation and complexity. It appears that some CH_4 is trapped in the N_2 and some is in separate patches on the surface where it is exposed to the atmosphere. Similarly, some of the CO that has been detected may occur as exposed surface outcrops. Because of Pluto's diurnal and seasonal cycles, the distribution of the N_2 and its contaminants is probably variable on both short and long time scales.

The profile of the N_2 spectral band suggest that the nitrogen on Triton occurs in the region of the , phase space (the transition temperature is 35.6 K), and that the temperature of the nitrogen ice is 40 (± 2) K at the present near-perihelion epoch (Stern et al., 1993; Tryka et al., 1993; Jewitt, 1994). Temperature changes of the N_2 ice with season may take it below the phase transition temperature and into the phase. N_2 has a cubic crystalline structure of higher density than N_2; transitions from one phase to the other may cause physical (or at least optical) disruption of the nitrogen ice on Pluto's surface.

In addition to the molecules so far identified on Pluto, the infrared spectra suggest that additional compounds remain to be found. In particular, other hydrocarbons may occur; their spectral features are in part masked by the strong CH_4 bands, but efforts are underway to identify additional molecular species. Furthermore, isotopes of C, O, and N may be identified with higher spectral resolution measurements.

Those regions of Pluto not covered by N_2 have a lower albedo, a distinctly red color, and a higher temperature, as suggested by IRAS data (Sykes et al., 1987). Albedo maps of Pluto, as well as thermal models of the temperature distribution, suggest that the darker areas are near the equatorial regions, with polar caps composed (from ground-based spectra and analogy with Triton) of N_2 ice. The composition of the darker areas is not known, but it may include refractory organic solids produced by photochemistry of the molecules found in the ice (and in the atmosphere), material accreted from outside sources, or products of cosmic ray bombardment and photochemical processes. Finally, patches of nearly pure methane probably exist on the surface at elevated temperatures compared to the nitrogen frost (Stansberry et al., 1996).

Charon's surface is less reflective than Pluto's. Spectroscopic observations show that it is largely (if not entirely) covered by frozen water plus some unidentified gray (neutral colored) component that is nearly uniformly distributed across the satellite's surface. (Buie et al., 1987; Marcialis et al, 1987). While the presence of H_2O is certain, additional ices could also be present. Quantitative models of the reflectance of Charon show that a large quantity of solid CO_2 and a substantial amount of CH_4 and CO on Charon are not excluded by the existing data; the exact amounts depend strongly upon the details of the scattering geometry (e.g., the dimensions of the grains) of the surface (Roush, 1994).

The presence of other volatile materials on both Pluto and Charon is of great interest in understanding the origin of these and other small bodies of the outer Solar System. The compositional relationship of this unique binary system to the neighboring Kuiper Belt of planetesimals bears on the origin and chemical evolution of the comets, the outer planets and their satellites. It is important that we establish the composition of the darker materials on both Pluto and Charon to learn if they are related to the organic materials imported to the Solar System from the nascent molecular cloud during formation or if they are produced over time on the surface by cosmic-ray bombardment or photochemistry.

The extreme seasonal cycle experienced by the Pluto-Charon pair affects the interaction of the surface volatiles and the atmosphere of Pluto. The interchange of material from surface solids to atmospheric gases during this cycle has been modeled theoretically but is not yet observationally constrained.

4.7. PLUTO'S ATMOSPHERE

4.7.1. *Some general considerations*

Information about Pluto's atmosphere comes from a variety of sources. Direct information was first obtained during the occultation of a 12th magnitude star by Pluto in 1988. Measurements of the composition and physical state of the surface also bear directly on the atmosphere because we believe that the composition and structure of the atmosphere is determined to a large degree by its interaction with the surface. Less direct information is obtained by comparing Pluto with Triton. Triton is roughly the same size as Pluto, and likely formed in a similar orbit around the sun (McKinnon, 1984; Goldreich et al., 1990). For these reasons, as well as because the atmospheres of both Triton and Pluto are predominantly N_2, Voyager observations of Triton should provide a good guide to the range of phenomena to be expected in Pluto's atmosphere. Finally, we can rely upon physical theories to help frame questions about Pluto's atmosphere, bearing in mind that specific predictions about the physical state of an unstudied atmosphere are difficult and likely to be unsuccessful. What we do know about Pluto suggests an atmosphere which is both varied and extreme in many ways. Because of the expected large variations in the surface temperature (a consequence of the observed albedo patterns and volatile distribution) the atmospheric structure near the surface is likely to exhibit large geographic variations: horizontal temperature variations may be as large as a factor of two (on Earth a 10% variation is considered large). There are suggestions, based on the occultation data, that the vertical temperature gradient in the atmosphere could be as steep as 20-30 K/km. The atmosphere contains at least three condensible species, namely (N_2, CO, and CH_4). The interplay between these atmospheric species and the associated surface ices should be complex, with an interesting analogy to CO_2 and H_2O on Mars. Pluto has the most weakly bound atmosphere in the Solar System and consequently the atmosphere which is lost most rapidly, relative to the atmospheric bulk.

When thinking about Pluto's atmosphere it is important to remember that the knowledge based directly on observations is limited and that in the history of outer Solar System exploration nature has repeatedly demonstrated an imagination superior to our own. The atmospheres in the outer Solar System have proved to be more varied and interesting than predicted by earthly investigators. It is extremely unlikely, for example, that the geysers on Triton could have been predicted (or that such a prediction would have been taken seriously by the scientific community). The same is likely to be true of Pluto. Planetary exploration remains an observational science, and a mission is needed in order to understand Pluto. The description below follows this point of view.

4.7.2. Thermal structure and composition

In 1988 Pluto occulted a 12th magnitude star (Hubbard et al., 1988; Elliot et al., 1989; Elliot and Young, 1991; Millis et al., 1993). Our knowledge of Pluto's atmosphere is based largely on observations of this event. The occultation and its implications have recently been reviewed by Yelle and Elliot (1995). A brief summary is given here. The occultation was observed by several ground-based and airborne observatories. Although much can be learned from the simultaneous analysis of the entire occultation data set (Millis et al., 1993), the data obtained with NASA's Kuiper Airborne Observatory (KAO) have the highest signal-to-noise ratio and supplies most of the basic information on the state of the atmosphere. The data along with model fits are shown in Figure 2. Both ingress and egress occultations were observed and, to within the accuracy of the data, the light curves appear to be identical. The occultation observations probe the atmosphere in the pressure region from several microbars to several tenths of a microbar and within this region there are clearly some changes in the structure of the atmosphere. An abrupt change in the slope of the light curve occurs at 1215 ±11 km, where the pressure is 2.33 ± 0.24 μbar. The nature of this change is discussed further below. We first describe the atmosphere above 1215 km because the structure in this region appears to be fairly simple.

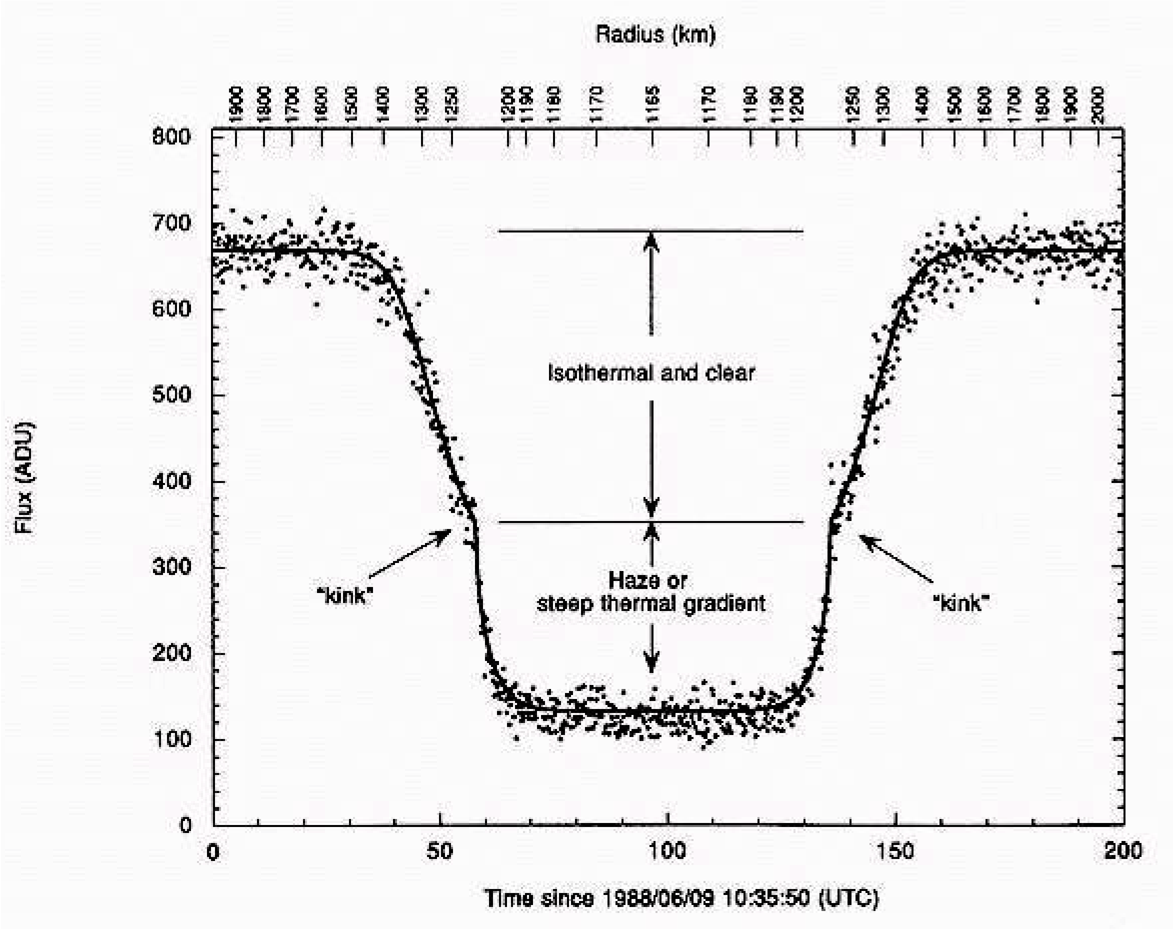


Figure 2. Data from the KAO observations of the 1988 occultation. The regions of the occultation well fit by an isothermal model and the location of the "kink" in the lightcurve are indicated on the Figure.

Middle atmosphere The occultation is sensitive to the ratio of temperature to mean molecular weight T/μ, which is directly proportional to the atmospheric scale height. Analysis of the KAO data at altitudes above 1215 km implies a value of $T/\mu = 3.63 \pm 0.33$. Because of the similarity of the ingress and egress light curves either this region of the atmosphere is globally uniform or the occultation, by happenstance, probed two separate regions with identical temperature profiles. Moreover, the temperature in this region appears to be approximately constant with altitude. The KAO data have been used to constrain the temperature gradient to be 0.05 ± 0.07 K/km/amu. To determine the temperature of the atmosphere it is necessary to know the mean molecular weight. There are two lines of reasoning that strongly imply that the atmosphere is predominantly composed of N_2. First, the atmosphere of Pluto is evolved from ices on its surface (Trafton and Stern, 1993). There is spectroscopic evidence for surface deposits of CH_4; N_2, and CO ice. Owen et al. (1993), from spectroscopic data, determined that N_2 is the dominant ice on Pluto's surface. At the relevant temperature N_2 has a vapor pressure an order of magnitude larger than CO and several orders of magnitude larger than CH_4; thus, as the most volatile and abundant ice on the surface it appears certain that N_2 will dominate the atmosphere and the mean molecular mass should be close to 28. Tryka et al. (1994) have used the temperature dependence of the N_2 band shape to estimate a temperature for the surface ice of 40 ± 2 K. This implies a surface pressure of 19-160 μbars. Although this is not a strong constraint on the surface pressure it does imply that the N_2 ice on the surface is warm enough to support a significant atmosphere. The depth of the atmosphere is discussed further below.

Second, a mean molecular weight of 28 implies an atmospheric temperature of 102 ± 9 K. This value is close to the CH_4 radiative equilibrium temperature calculated by Yelle and Lunine (1989), suggesting that the atmosphere contains enough CH_4 to control the thermal structure (Yelle and Elliot, 1995). The CH_4 abundance required for this is on the order of 1% (Yelle and Lunine, 1989; Strobel et al., 1995). Lellouch (1994) points out that cooling by CO could be important and argues that the CH_4 abundance is small: he suggests that the elevated temperatures are due to aerosol heating. Young (1994) has inferred the column abundance, η, of CH_4 in the atmosphere through analysis of high spectral resolution measurements of CH_4 absorption bands in the near infrared region of the spectrum. She determines a value of η = 1.2 (+3.15, -0.87) cm- amagat, which corrresponds to a CH_4 partial pressure of 9.8 (+2.5, -0.7) x $10^{-2}\mu$bar . Since the N_2 abundance in the atmosphere is not well known, it is not possible to tightly constrain the CH_4 mole fraction. Clearly, determination of the relative abundances of N_2, CH_4, and CO is critical to an understanding of the thermal structure of Pluto's atmosphere. At the present time there are no direct observations of CO in Pluto's atmosphere. CO ice does reside on the surface, however (Owen et al., 1993) and therefore CO should be present in the atmosphere also. The abundance is difficult to predict with the data available. On Triton, the atmospheric CO is undersaturated by several orders of magnitude, probably because the CO ice is bound in an N_2 matrix (cf. Yelle et al., 1995). Argon and other noble gases are cosmically abundant and sufficiently volatile to be present in Pluto's atmosphere if their ices exist on the surface. Because of the lack of spectral features, upper limits on the possible abundance of these ices are not available.

Lower atmosphere The atmospheric structure below 1215 km is more complicated and less well understood. Elliot et al. (1989) suggested that the change in slope of the light curve could be due to the abrupt onset of an aerosol layer at 1215 km; Eshleman (1989) and Hubbard et al. (1990) suggested that the break in the light curve could be due to a strong temperature gradient in the atmosphere, such as that present in the thermal inversion model of Yelle and Lunine (1989). In either case the lower atmosphere of Pluto is obscured and the net result is that the surface pressure of Pluto's atmosphere is poorly constrained. Stansberry et al. (1994) demonstrate that a troposphere, i.e. a near-surface atmospheric region with a negative temperature gradient, of up to 40 km deep would not produce noticeable effects in the occultation data. Therefore, it is possible that the surface of Pluto lies many tens of kilometers below the level probed by the occultation. The best upper limit on the surface pressure comes from the temperature determination of Tryka et al. (1994); their warmest temperatures correspond to a surface pressure of 160 μbar; thus, the surface pressure lies between roughly 3 and 160 μbars. Since the surface is much colder than the atmospheric temperature of 100 K, there must be a region of strong positive temperature gradient. The shape of the temperature profile is not known at the present time. It is likely that there are geographic variations in the near surface vertical temperature profile related to the observed albedo variations on the surface, but there are no observational constraints on these variations.

The structure of Pluto's lower atmosphere is an outstanding question. If the change in slope of the KAO light curve at 1215 km is due to a temperature gradient, then the gradient is likely to be large.

Stansberry et al. (1994) estimate that a gradient of 20 K km is required, although this value depends on the assumed shape of the temperature profile. Similarly, if the change in slope is due to aerosol absorption, the aerosols are far more abundant than expected (cf. Yelle and Elliot 1995) posing a different puzzle. Even our limited knowledge of Pluto's atmosphere is sufficient to distinguish it among atmospheres in the Solar System.

The surface pressure, though ill-determined, is on the order of tens of microbars, which places it in the same class as Triton's atmosphere. Though small, this surface pressure is sufficient to support a host of interesting and observable physical processes in the atmosphere. However, Pluto's atmosphere appears to be under radiative control, at least in the 1 μbar region, which is very different from Triton, whose lower atmosphere is essentially at the same temperature as the surface. The large discontinuity between the surface temperature and atmospheric temperature is unique in the Solar System and it is very unlikely that all of the implications of this situation are understood at the present time.

4.7.3. *Atmospheric chemistry*

In addition to the species supplied by the evaporation of surface ices Pluto's atmosphere should contain molecular, atomic, and ionic species produced by photochemistry. The situation should be similar to that on Triton, with important differences due to the larger CH_4 abundance, potentially different CO abundance, distinct energetic particle environments, and disparate atmospheric temperatures. The chemistry of Triton's atmosphere has proved to be complex (cf. Summers and Strobel, 1995). The main feature is a very close connection between the neutral photochemistry of the lower atmosphere and the ion-neutral chemistry in the ionosphere. The presence of CH_4 and N_2 in the atmosphere implies the presence of photochemically produced species such as H; N; HCN; C_2H_4, along with other hydrocarbons and nitriles. Photochemical model calculations for the abundance of minor constituents have been presented in Summers and Strobel (1995). These exploratory calculations are a useful way to study the physical and chemical processes in Pluto's atmosphere. However, there is a lack of observational constraints on the minor constituents and uncertainties in basic atmospheric parameters such as surface pressure, bulk composition, vertical mixing rates, aerosol content, etc., and uncertainties in the values of reaction rates at low temperature. In consequence, a wide range of results are possible and the models do not have much predictive capability. Nevertheless, although the abundance of minor constituents cannot be predicted with confidence, the Summers and Strobel models probably do provide a good guide to the types of minor constituents likely to be in the atmosphere. An illustrative calculation, showing density profiles for some of the photochemically produced species is presented in Figure 3.

Pluto presents another example of an interesting problem in the evolution of volatile atmospheres in the outer Solar System. CH_4 is irreversibly lost from the atmosphere because photolysis liberates H and H_2, which rapidly escape. The loss rate for atmospheric CH_4 due to photolysis is on the order of ten thousand years, much shorter than the age of the Solar System. Either the initial endowment of CH_4 ice on Pluto's surface is sufficient to resupply the atmosphere over the age of the solar system, or CH_4 must be supplied from a reservoir in the interior. If the latter possibility is correct, it implies the existence of geological processes which transport CH_4 from a subsurface reservoir to the surface. Another consequence of photolysis is the production of higher order hydrocarbons (such as those predicted by the chemical models mentioned above) which eventually condense and end up on the surface, yet no other hydrocarbon species have been detected. These same questions appear in slightly different guises on both Triton and Titan. More thorough searches for photochemical products are required and the theoretical mechanisms of photochemistry in the atmosphere need to be observationally tested.

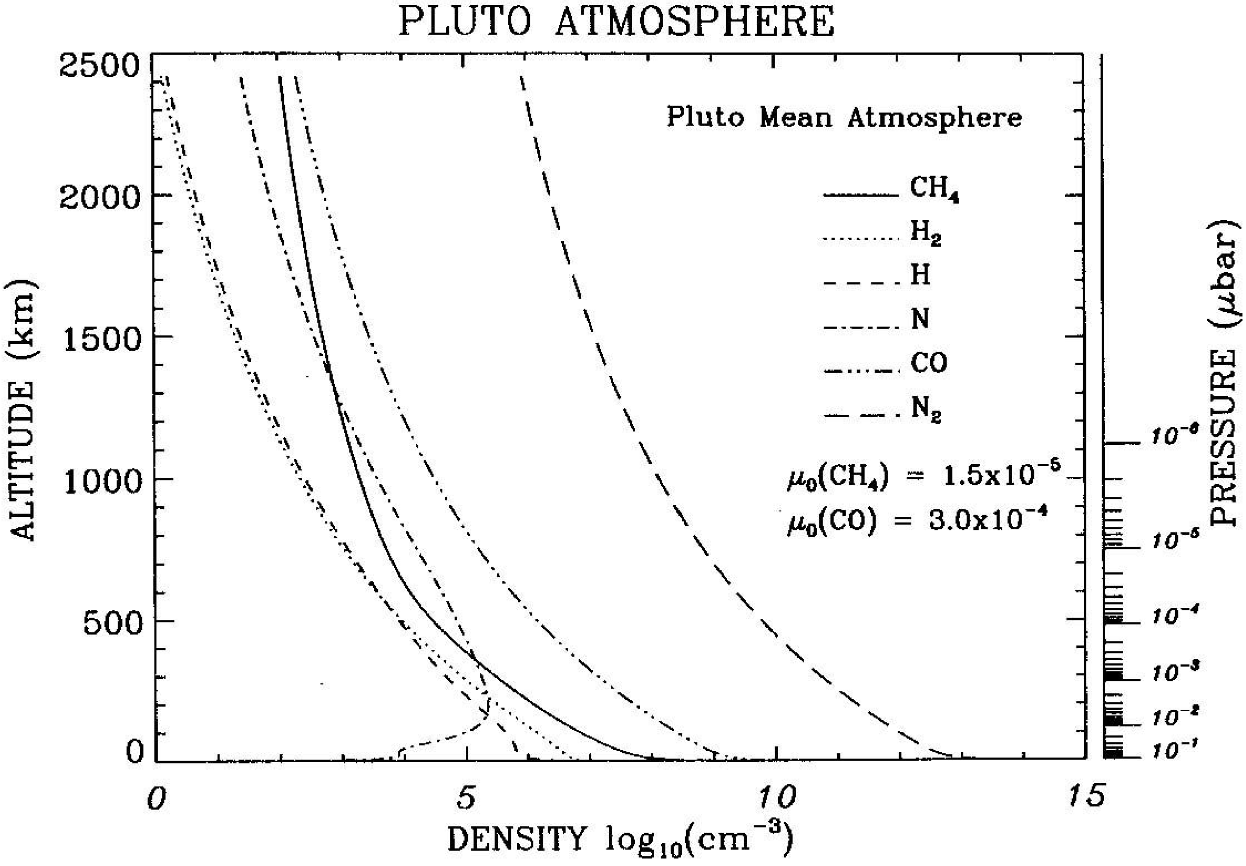


Figure 3. Calculations of the composition of Pluto's atmosphere from Summers and Strobel (1996). These photochemical calculations assume that the atmosphere is predominantly N_2 with small amounts of CH_4 and CO; the distance of Pluto from the sun is set at 40 AU, yielding a surface pressure less than that derived from the 1988 stellar occultation which occurred near perihelion.

4.7.4. *Atmospheric circulation and volatile transport*

Because Pluto's atmosphere is evolved from ices on its surface, volatiles are transported through the atmosphere in response to diurnal and seasonal changes in solar insolation. These winds are thought to carry sufficient energy to maintain the surface deposits of N_2 ice at all locations on Pluto at a single common temperature (Trafton and Stern, 1983; Spencer et al., 1995). Groundbased maps of Pluto exhibit a bright region near the southern pole (Young and Binzel, 1993; Buie et al, 1995); it is tempting to identify this feature with a polar cap of N_2 ice. There are also dark regions on the surface, which are probably devoid of N_2 ice.

The N_2 deposits on Triton should migrate over the surface of the body in response to seasonal forcing. Understanding the albedo patterns on Triton's surface has proved difficult, although a number of physical processes have been identified (cf. Yelle et al., 1995). Studies have been hampered by the lack of information on compositional variations across the surface: Voyager carried no instruments capable of spectroscopic determination of surface ice composition and therefore composition had to be inferred from the visible albedo with very ambiguous results. This will not be a limitation on Pluto given the spacecraft strawman payload. There have been several preliminary (necessarily theoretical) studies of volatile transport on Pluto (Hansen and Paige, 1995; Spencer et al., 1995). The goal of these studies is to understand the distribution of volatiles on the surface through the study of seasonal transport processes, i.e. to understand the formation of polar caps. One of the difficulties faced by studies of Pluto's seasonal cycles is that it has proved difficult to understand the apparently complex distribution of volatiles on Triton revealed by Voyager 2.

Despite the present difficulties in understanding the volatile distribution on Triton, several signatures of seasonal transport processes are evident. Wind streaks were observed on the surface at virtually all locations in the southern hemisphere (Hansen et al., 1990). The streaks were oriented predominantly to the northeast, which is consistent with the direction expected for seasonal volatile flow near the surface. Several different types of cloud features were observed in the atmosphere and in several cases the movement or orientation of the clouds allowed the inference of wind directions (Hansen et al., 1990). Consideration of all of these data along with some simple dynamical concepts has resulted in a fairly complete description of Triton's circulation patterns (Ingersoll, 1990; Yelle et al., 1995). It is possible and probably likely that the same types of signatures will be evident on Pluto's surface and in the atmosphere.

4.7.5. Cloud formation and aerosols

For the purposes of discussion we define clouds as particulates in the atmosphere created by the condensation of one of the major atmospheric species; thus, clouds on Triton probably consists of N_2 ice and clouds on Pluto could consist of CH_4, CO, or N_2 ice. Hazes may be formed by photochemical processes in the atmosphere, similar to those that on Earth produce smog in major urban centers. Although condensation of a photochemical product species is probably responsible for the creation of aerosols, the particulates so formed differ in character from those formed by condensation of a main constituent. At least that seemed to be the case on Triton, where Voyager 2 saw clearly defined discrete clouds scattered over the southern hemisphere and a pervasive diffuse haze that permeated the entire atmosphere except for one particular and curious location (cf. Yelle et al., 1995). All of the atmospheres in the outer Solar System contain hazes and Pluto should be no exception. As mentioned above, the hazes are believed to be photochemical in origin (Elliot et al., 1989), but further study is required to determine the mechanism by which the hazes form, the potential for supersaturation, and the role of aerosols in photochemistry. If Pluto possesses a troposphere, as suggested by Stansberry et al. (1994) then it is likely that clouds also form. The repeatability of Pluto's rotational lightcurve argues against a thick planetwide cloud layer (i.e Venus like) but clouds of the type observed in Triton's atmosphere could be present.

4.7.6. Temporal variations in the atmosphere

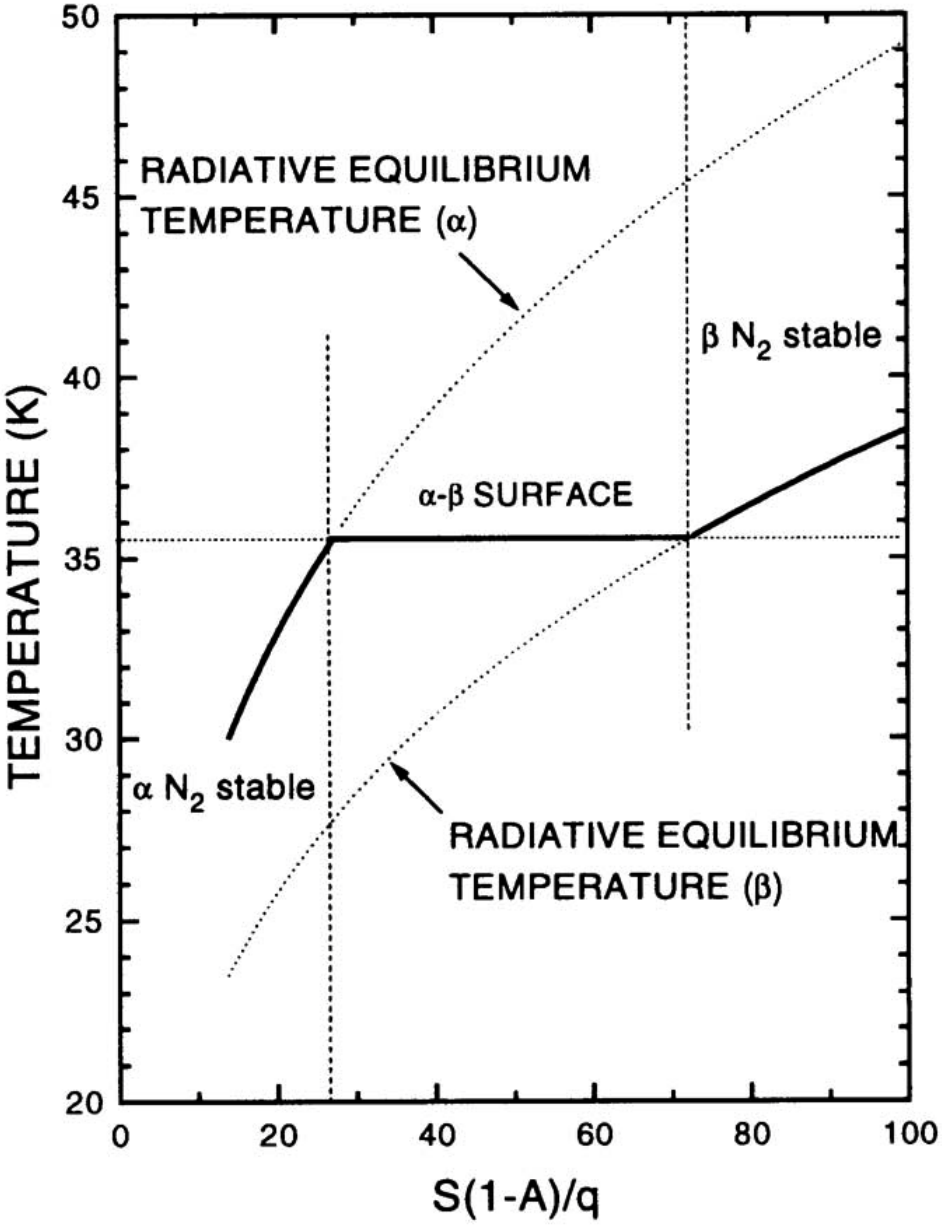
Temporal variations in Pluto's atmosphere are potentially very large, because the large eccentricity of its orbit carries it from 29 to 49 AU, which corresponds to a 41% drop in insolation from perihelion to aphelion. If, for example, Pluto is assumed to be covered with N_2 ice with an albedo of 0.8, and it is further assumed that the emissivity of the ice has a value of 0.75 which is constant with temperature, then the surface temperature should vary from 34-42 K and the surface pressure should vary from 1-40 μbar from aphelion to perihelion (Stern et al., 1993). Stansberry and colleagues at NASA Ames have argued that changes in the emissivity of surface nitrogen ice as it undergoes a low temperature phase transition could buffer the atmosphere and prevent substantial collapse (Figure 4). It is clear from both theory and observation that the temporal behavior of Pluto's atmosphere is poorly understood and might be complex. It is equally clear that, as Pluto moves away from perihelion, the next couple of decades are an important, perhaps crucial, time to study any atmospheric changes that might take place. Should Pluto's atmosphere decrease in mass over time, its various properties could change dramatically, as suggested in figure 5, prepared by M.S. Summers (unpublished).

4.7.7. *Atmospheric escape*

As a consequence of its relatively small size and relatively high atmospheric temperatures, Pluto has the most extended and most weakly bound atmosphere in the Solar System. In a hydrostatic atmosphere, the variation of pressure with altitude is governed by the ratio of gravitational protential energy to kinetic energy, $\lambda = GMm/kTR$. On Pluto the value of lambda inferred from the occultation is 22.4 ± 0.8, nearly a factor of 3 smaller than for any other atmosphere. This implies that Pluto will have a greatly extended atmosphere which is rapidly escaping to space. In particular, the hydrostatic approximation no longer applies because outflow velocities are large enough that inertial terms in the momentum balance equation are important. The outflow has the effect of cooling the thermosphere to temperatures below that which would occur in a hydrostatic case. Jean's equation for the atmospheric escape rate is not valid for Pluto and the hydrodynamic equations must be solved to determine the atmospheric structure and the Pluto Express: Report of the Science Definition Team escape rate.

Although hydrodynamic escape is believed to be an important process in the evolution of many atmospheres, Pluto represents the only non- hydrostatic atmosphere in the present day Solar System and we have a unique opportunity to study this phenomenon.

Figure 4. An example of a possible buffering of Pluto's atmosphere by surface ices, from John Stansberry at NASA Ames and colleagues. Plotted is radiative equilibrium temperature versus absorbed solar insolation (here S is solar flux, A albedo, and q a factor associated with the distribution of reradiated solar flux). The two different nitrogen phases, and N_2 , have differing emissivities and hence different radiative equilibrium curves. Because of this, a possible buffering of the surface temperature around the phase transition temperature (35 K) is possible.



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4.8. THE INTERACTION OF PLUTO WITH THE SOLAR WIND

Pluto is similar to Triton in mass, radius, and, currently, surface pressure (Stern, 1992). However, Triton's atmospheric structure and plasma environment are quite different, and the thermal escape rate is negligible. The surrounding plasma environments are also quite dissimilar. In spite of the Voyager 2 flyby through the Neptune system, the nature of the interaction of Triton with its plasma environment was not established due to lack of a close downstream approach by the spacecraft (Neubauer et al., 1991), although a substantial ionophere was detected (Tyler et al., 1989; Majeed et al., 1990; Strobel et al., 1990).

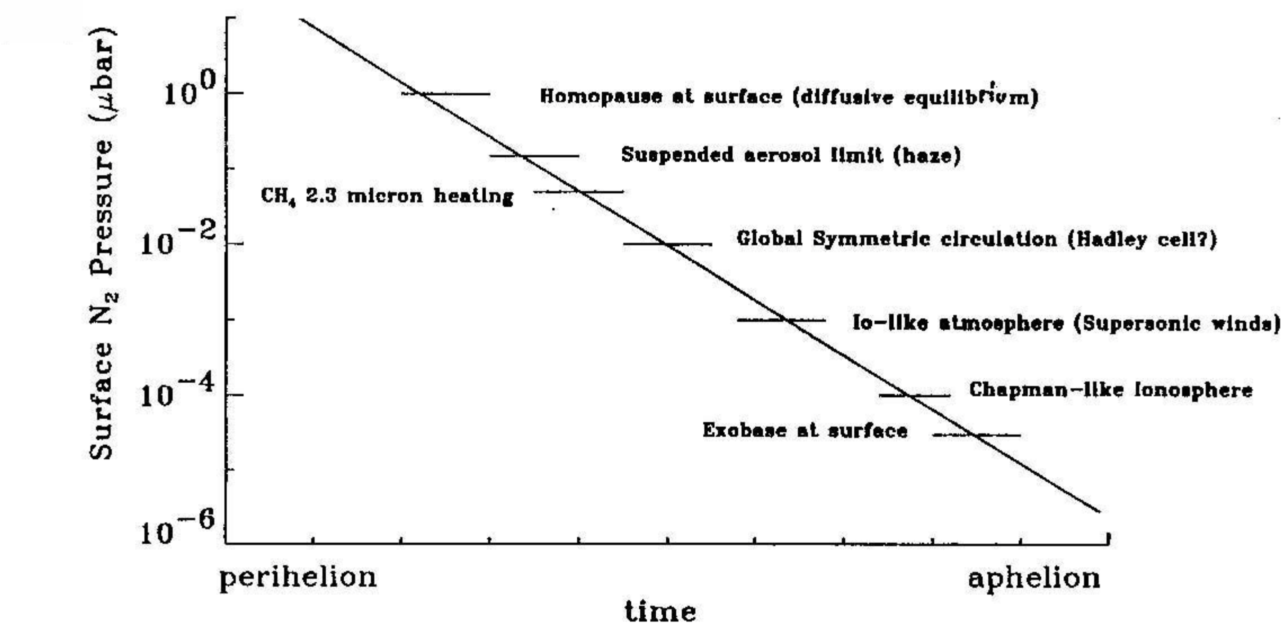

Figure 5. Changes in the characteristics of Pluto's atmosphere based on a possible decrease in its size as Pluto moves toward aphelion. Key to each of the threshold levels: Homopause is the level at which molecular species separate according to mass; CH_4 heating refers to the minimum density at which methane is an effective near-infrared absorber; Hadley cell and Chapman-like ionosphere are described at length in Chamberlain and Hunten (1987); exobase is the level at which the atmosphere becomes collisionless. Figure prepared by M.S. Summers.

Titan, the other small world with a substantial atmosphere, is known to interact with the plasma in Saturn's magnetosphere (McNutt and Richardson, 1988 and references therein). Again there are substantial differences from Pluto, and, at the current epoch, the interaction of Pluto with the solar wind plasma is truly unique in the Solar System.

The primary difference between Pluto and these other worlds is the suspected high escape rate of Pluto's atmosphere. This hydrodynamic escape is powered at least partly by the mesospheric absorption of solar EUV and FUV radiation, and potentially has significant consequences for the interaction of Pluto with the solar wind (precipitation of charged particles could also play a role in powering the atmospheric escape). The nature and extent of the interaction has, in turn, consequences for atmospheric evolution and possible surface effects.

The extreme cases of the interaction of the solar wind with neutral atmospheres range between a gravitationally bound atmosphere, e.g. Venus (Luhmann, 1986), and a freely evaporating atmosphere such as found during spacecraft encounters with comets (Neugebauer, 1990). In the former case, an ionosphere is present and the interaction is governed by ionospheric chemistry and dynamics. In the latter case, the interaction is through the mass loading, deceleration and deflection of the solar wind via ionization and subsequent pick-up and gyration of the outflowing neutrals.

The idea of an atmosphere of Pluto (Trafton, 1980) was only recently settled by the stellar occultation of 1988 (Hubbard et al., 1988; Elliot et al., 1989). The inferred hydrodynamic escape of Pluto's atmosphere (McNutt, 1989 and references therein) suggests Pluto resembles a “heavy comet” with significant mass-loading of the solar wind over an extensive region around the planet (Bagenal and McNutt, 1989; Kecskemety and Cravens, 1993). The “break-point” for the comet analogy can be estimated from fluid theory (Galeev et al., 1985) as a mass loading rate of 1.5×10^{27} *molecules* s^{-1} (Bagenal and McNutt, 1989). If the true escape rate is much less than current estimates of 2.3×10^{27} to 3.4×10^{28} *molecules* s^{-1}, Pluto's ionosphere could deflect the solar wind in a Venus-like interaction confined to a region much closer to the planet.

Depending upon the exact nature of this interaction, measurements of the solar wind Pluto-ion interaction region can yield a sensitive measure of the escape rate of Pluto's atmosphere and whether it is in a state of supersonic hydrodynamic escape. The accuracy of this determination will depend itself upon the nature of the interaction (comet-like, Venus-like, intrinsic magnetic field - see below).

The gyro radii of both solar wind ions and picked-up atmospheric ions will be very large due to the weak interplanetary magnetic field (0.1 nT) at 30 AU. The gyroradius for methane pick-up ions near Pluto is $\approx 500\ R_{Pluto}$. Molecular nitrogen ions (or carbon monoxide ions) will have pick-up gyroradii roughly twice as large.

The thickness of an upstream bow shock would be 10R , comparable to the size of the interaction region. With this scaling, a distinct bow shock is unlikely and kinetic effects must be included in order to model the solar wind interaction realistically. In fact, the gyroradii are sufficiently large compared with the size of Pluto that the interaction is probably unique in comparison with all cases studied before except for the active AMPTE-ion releases in the solar wind. This situation is actually quite different from a cometary case at 1 AU with a high gas production rate such as at comet Halley, and the break point estimated above may also change substantially in the Pluto case. Theoretical work suggests that no bow shock forms due to the kinetic features of the interaction (Sauer et al., private comm.).

Given our lack of knowledge of the interaction, we can at least get a feel for possible scenarios by using some concepts from fluid theory.

As the solar wind flow penetrates the escaping neutral outflow, local ionization and subsequent pick-up decelerates the solar wind, leading to stagnation when the newly picked-up cometary ions dominate the composition. In the cometary plasma region the flow speeds are reduced to a few km s^{-1}, the magnetic field is compressed, collisions become increasingly frequent and charge-exchange cools the plasma. Near the planet the gyroradii will decrease somewhat as the magnetic field is compressed by the “obstacle” formed by the pickup process.

For methane and typical parameters, the scale length for a fluid-like standoff region is

$$\frac{R_{so}}{R_{\text{Pluto}}} = \frac{Q_{esc}}{Q_o}$$

where $Q_O = 1.5 \times 10^{27}$ *molecules* s^{-1}. Inclusion of charge exchange and impact ionization will make R_{SO} larger. Thus, an escape rate of ~ 10^{28}, which would be comparable to the outgassing of Comet Giaccobini-Zinner at 1 AU (Mendis et al., 1986) and consistent with upper limits derived by Hunten and Watson (1982), Hubbard et al. (1989) and the more optimistic cases of McNutt (1989), would produce $R_{SO} \sim 6R_{\text{Pluto}}$.

Drawing further upon the comet analogy, consider the pickup of CH_4^+ produced by the photoionization of methane outgassing from Pluto. In the transition region at distances of 10^4 km from Pluto, pickup ion densities can be as high as $>10^{-4}$ cm^{-3}, distributed in partial shells in velocity space. Corresponding energy spectra may exhibit differential fluxes greater than 10 cm^{-3} s^{-1} keV^{-1} (Kecskemety and Cravens, 1993).

If the atmospheric escape flux is less than 1.5×10^{27} *molecules* s^{-1} then the solar wind will interact more directly with the planet's atmosphere, similar to the cases at Venus and Mars and to the magnetospheric interaction with Titan. The Venus case is the best-studied because of the extensive Pioneer Venus data but, the cases of Mars or Titan are probably more appropriate analogies.

Pluto's ionosphere may resemble that of Triton in the absence of magnetospheric electron input (e.g. Ip, 1990). The expected ionospheric pressure is small, but it is comparable to the ram pressure of the solar wind at 30 AU Thus, one expects a large interaction region compared with the size of the planet, with $R_{\text{ionopause}} \sim 1.5\ R_{\text{Pluto}}$ (for the Titan-like case). This is actually more reminiscent of Titan where $R_{\text{ionopause}} \sim 1.4 - 1.8R_T$ and Mars (where $R_{\text{ionopause}} \sim 1.15R_M$). In this scenario, scavenging of the atmosphere by the solar wind may be significant over the lifetime of the Solar System.

In an exploratory mission one cannot a priori rule out surprises. Pluto could possess an intrinsic magnetic moment capable of standing off the solar wind. A surface field of only ≈ 10 *nT* would suffice to stand off the solar wind (average conditions) to the exobase. Magnetization comparable to that found in some meteorites could lead to a convection-dominated magnetosphere that stands off the solar wind at several Pluto radii above the surface.

For a magnetosphere to extend to Charon's orbit at 17 R_{Pluto} , the surface field must be $B_O >$ 3700 nT . Such a hypothetical magnetosphere could be similar to that of Mercury (Russell et al., 1988), but with no belts of trapped radiation and plasma flows induced by the magnetic interaction with the solar wind.

The presence of radiation belts and accelerated particles remains problematic in this scenario. Given the low power input available from the solar wind at such large heliocentric distances, it is not clear to what extent magnetospheric particles could be energized (Kivelson, private comm., 1993); cosmic ray albedo neutron decay particles may be present, at least.

For example, the asteroids Gaspra and Ida encountered by the Galileo spacecraft on its way to Jupiter, are intermediate in size between the local electron and ion gyroradii. The resulting interaction with intrinsic asteroidal magnetic fields should be whistler-like. Such signatures may have been actually detected by the Galileo magnetometer (Kivelson et al., 1993). This magnetosphere would persist throughout Pluto's orbit, even if Pluto's atmosphere freezes out as it approaches aphelion. Any remnant magnetization of Charon is likely to be less than that of Pluto due to the relative sizes. Charon is likely to either be exposed directly to the solar wind flow or to a plasma modified by the interaction of Pluto with the solar wind.

Bombardment of methane ice by energetic (10 keV to 100 keV) protons leads to carbon enrichment, and hence darkening of the ice-bearing material, for fluences greater than $10^{16}\ cm^{-2}$. Such irradiation has been suggested to be responsible for the dark color of the moons and rings of Uranus (Lanzerotti et al., 1987). The coloration of both Pluto and Triton suggest irradiated ice cover on the respective surfaces with color persistence suggesting resurfacing on time scales similar to those required for accumulation of a 10^{10} erg cm^{-2} charged particle dose; differences in the Pluto and Triton spectra suggest the visibility of a greater amount of irradiated material at Pluto (Thompson et al., 1987).

If Pluto undergoes a comet-like interaction, pick-up ions will be produced in the upstream solar wind which can impact Pluto's atmosphere. (If the interaction region is sufficiently large they will also impact Charon). Actual production of color changes at the surface is problematic: the energies of the ions are probably not sufficient to penetrate the atmosphere and reach Pluto's surface at this time. As the outgassing rate decreases, penetration of ions to the surface will increase, but their intensity will drop. If Pluto possesses an intrinsic magnetosphere, then sufficient fluxes of energetic ions and electrons may be present to affect the surface color, depending upon the particle energies reached (Johnson, 1989).

Scavenging of the atmospheres surfaces of Pluto and or Charon may be significant over Solar System time scales. If Pluto's atmospheric escape rate Pluto is low, then Charon is embedded in the solar wind, receiving $2\times10^{4} - 2\times10^{6}$ protons $cm^{-2}\ s^{-1}$ (of kinetic energy ~ 1 keV). For expected atmospheric escape rates from Pluto pick-up fluxes at Charon's orbit could be about 10 kg of sputtered water over the course of a year. This additional source of material would contribute to the local mass loading and general escape of material from the Pluto Charon system.

Voyager and Pioneer measurements show that in the outer heliosphere the solar wind seems to settle into a steady pattern of a strong stream lasting a few days and repeating each 26-day solar rotation period (Belcher et al., 1993). For a steady atmospheric escape flux (say $10^{28}\ \mathrm{s}^{-1}$) the corresponding 1 variation in the size of the comet-like interaction region R is ~3.9 to 24 R for time scales of a few days (comparable to Pluto's rotation and Charon's orbital period of 6.4 days). This effect may be amplified or softened as the variations of EUV forcing of the upper atmosphere change the atmospheric escape flux on a similar timescale. If the atmospheric escape flux is low and the solar wind impinges directly on the ionosphere, then the size of the interaction region will also change in response to the solar wind ram pressure, though less dramatically than in the cometary case (because, effectively, the ionosphere is much less compressible).

Perhaps the most intriguing aspect of the Pluto/Charon system is the possibility of major changes over the 248-year orbital period due to the high orbital eccentricity. If the atmosphere does not completely freeze out it will still undergo radical compositional changes. A very weak atmosphere (either now or as the planet recedes from perihelion) could lead to complete absorption of incident plasma, as at the Moon, and the production of a sputtered exosphere. If Pluto has a strong magnetic field ($B_O > 3700\ nT$) then a magnetosphere will remain around Pluto and Charon throughout their orbit. In the absence of a significant intrinsic magnetic field the solar wind interaction at Pluto might undergo a transition from “cometary” to “planetary” to “lunar” behavior as the escape flux decreases. If the interaction scale for the cometary interaction always exceeds that for an ionospheric interaction and the ionosphere ceases to provide adequate thermal pressure as the mass-loading weakens on receding from the sun, then the Pluto interaction may evolve directly from comet-like to Moon-like.

Regardless of which, if any, of these scenarios and inferences is correct, the interaction of Pluto with the solar wind is likely to be unique in the Solar System. Given what little we do currently know about the atmosphere, detection and characterization of the interaction interaction region at the current epoch will provide good estimates of the overall atmospheric escape rate and implications for the evolution of the Pluto/Charon system.

4.9. KUIPER DISK OBJECTS AND PLUTO'S RELATIONSHIP TO THEM

Recently, trans-Neptunian bodies have been discovered that are widely believed to constitute the long-sought Kuiper Belt. This is a primordial disk of planetesimals beyond Neptune which have survived since the formation of the planetary system. The Belt is of scientific interest on many levels. It is the suspected source of the short-period comets. Trans-Neptunian objects may contain some the least processed Solar System material, and thus ultimately provide a window on processes operative in the epoch of planet formation. Mutual collisions in the Kuiper Belts of other stars are suspected sources of circumstellar dust, perhaps providing a link with such systems as the unexpectedly dusty main-sequence star Pictoris. Collisions in our own Kuiper Belt may also be a source of observable dust: COBE data are being independently analyzed in search of the anticipated low temperature diffuse thermal emission.

The discovery of the trans-Neptunian objects of the Kuiper Belt, coming on the heels of the Voyager explorations of the giant planets and their satellites, has sparked continued scientific vigor in the study of the deep outer Solar System, and provided grist for the mills of those interested in the origin of such disparate entities as Pluto, Triton, the Centaurs (the type member of which is the asteroid 2060 Chiron), comets and the planetary system itself. In addition to extensive observational efforts on moderate to large aperture telescopes, several theoretical studies have been sparked by the discovery of the Belt.

The remarkable orbital similarity between Pluto and some of the newly detected objects has provoked new work on the origin of that planet. Dynamicists are beginning to address the mechanism of capture into the 3:2 mean-motion resonance with Neptune. One result of the new work is the necessity to understand the relationship of Pluto to the smaller transNeptunian objects. Further the Kuiper Belt is a dynamically plausible source for short period comets, opening the possibility of a link between large outer Solar System solid bodies (such as Pluto and Triton) and short- period comets as the planetesimals from which they formed.

The key features of the Kuiper Belt are:

1. At the time of writing, 28 trans-Neptunian bodies exceeding 100 kilometers diameter (in addition to Pluto and Charon) have been directly observed from ground-based telescopes, all with low inclination orbits and small to moderate orbital eccentricities (Jewitt and Luu, 1993, 1995). Additionally, a population of smaller, perhaps comet-sized bodies moving consistent with Kuiper Belt orbits have been reported using Hubble Space Telescope data.

2. The orbits of many trans-Neptunians cluster near the 3:2 mean-motion resonance with

Neptune at a = 39 AU. It is likely that these objects are stabilized against Neptune perturbations by the resonance, much like Pluto. Other objects (e.g. 1995 DA2 and 1995 DB2) may be in the 3:4 resonance, although further astrometry will be needed to prove this.

3. The total number of Kuiper Belt objects larger than 100 km diameter in the 30 AU to 50 AU heliocentric distance range is about 35,000 (Jewitt and Luu, 1995). If recent Hubble Space Telescope observations are correct, the number of km sized and larger bodies may approach 1 billion.

4. The Kuiper Belt is the suspected source of the Jupiter-family short- period comets (SPCs). These small, ice-rich bodies have dynamical and physical lifetimes that are short compared to the age of the Solar System. If a steady state population is to be maintained, the comets in the inner Solar System must be resupplied from a longer-lived source elsewhere. While it has long been thought that SPCs are captured from long-period orbits by the action of the gas giant planets (especially Jupiter), this explanation has recently been shown to be invalid. In particular, the highly anisotropic distribution of orbital inclinations of the Jupiter-family SPCs argues for a flattened (disk-shaped) source, exactly as is observed among the Kuiper Belt objects (Duncan et al., 1988). Therefore, in the presently accepted view, the long-period comets are eroded from the Oort Cloud by external gravitational perturbations, while the SPCs have a separate and distinct source in the trans-Neptunian region. A mission to the Kuiper Belt therefore is a mission to the birth site of the comets.

5. The Kuiper Belt is likely a remnant of the much more extensive (and long gone) protoplanetary disk of gas and dust from which the solid objects of the Solar System formed, a conclusion which has been strengthened by very recent dynamical simulations (Duncan et al., 1995).

6. With the density of 100 km diameter Kuiper Belt objects being of order 1 per AU 3, the characteristic separation of these bodies is of order 1 AU. This means that, without any extra efforts on the part of Pluto Express, the post-Pluto encounter trajectory would pass (on average) about 1 2 AU from one or more large Kuiper Belt Objects. This is a pessimistic estimate of the distance of closest approach for two reasons. First, there will be many opportunities (roughly one for each year of flight) for close encounters along the spacecraft trajectory in the years following the Pluto flyby. It is likely that several of them will occur at distances considerably smaller than 1 AU from the spacecraft. Second, and more importantly, Pluto Express will contain propellant sufficient to permit the spacecraft to be steered towards known Kuiper Belt objects. Accordingly, one or more post-Pluto encounters with objects in the Kuiper Belt almost certainly will be possible (encounters prior to arrival at Pluto are ruled out by the tight requirements imposed on the Pluto encounter geometry).

4.10. ORIGIN OF THE PLUTO-CHARON BINARY

The origin of the Pluto-Charon binary itself was recognized as a significant problem almost as soon as Charon was discovered by Christy and Harrington (1978). The noteworthy aspects of the binary are: (i) the small, 2:1 size ratio noted above; (ii) the complete tidal evolution of the system exhibited in the spin:spin:orbit synchronicity of Pluto's rotation period, Charon's rotation period, and Charon's orbital period; (iii) the high specific angular momentum of the system, which is close to the stability threshold for a spinning body; and (iv) the dissimilarity of Pluto and Charon with regard to their surface appearances, compositions, and perhaps their bulk densities.

These constraints have been considered by various workers, including McKinnon (1984; 1989a), Peale (1986), Simonelli et al. (1989), Stern (1991), and Levison and Stern (1995). The specific angular momentum of the system does not permit either a fission or co-accretion origin. The only origin scenario for the binary which appears to satisfy all of the available constraints (as for the Earth-

Moon system) is characterized by a “giant” collision between Pluto and some object several hundred to perhaps 1000 km in diameter. According to this formation scenario for the binary, the collision spalled enough material from Pluto and into orbit around it to generate Charon. Once Charon formed, it tidally evolved to its present orbit in ~ 10^7 years. Charon's surface color, albedo, and composition are believed to result from the much more effective role of atmospheric escape on Charon (Trafton et al. 1988), which led to a rapid loss of volatiles, and the subsequent darkening of the remaining, H_2O-ice lag deposits (cf., also Johnson 1989; Stern 1990). Charon's surface properties may also in part be related to its possibly-different internal volatile fraction, which itself may be related to the impact parameter and energetics of the giant collision.

An important qualititative difference between the Pluto-Charon and Earth-Moon giant-impacts is that the relative collision velocities, and hence impact energies of the Pluto-Charon event, were much smaller. This enormously ameliorated the resultant thermal effects at Pluto (McKinnon 1989b). Thus, whereas the Earth may have been left molten by the Mars-sized impactor necessary to have created the Moon, the proto-Charon impactor would probably only raise Pluto's global mean temperature by no more than 50-75 K. This is insufficient to melt either body, but may have been sufficient to trigger internal differentiation. It would have also produced a substantial transient, post-impact, hot, volatile atmosphere with intrinsically high escape rates, fractionating Pluto's present-day volatile content (cf. McKinnon 1989b; Lunine and Nolan, 1992).

If Pluto and some proto-Charon impactor did form in heliocentric orbit, why should these two objects, alone in over 10^3 AU^3 of space, “find” each other in order to execute a mutual collision? That is, the impact hypothesis fails to explain the fact that the collision producing the impact was highly unlikely, if Pluto and proto-Charon were the only large bodies in the 30-50 AU region. McKinnon (1984) was the first to discuss this point. Later, Stern (1991) pointed out that this issue, as well as the capture of Triton from heliocentric orbit, and the tipping of the obliquities of Uranus and Neptune could all be rationalized if Pluto and proto-Charon were members of a large, ancient population of some ~300-3000, small ($10^{24.5\text{-}25.5}$ g) precursor objects present during the accretion of Uranus and Neptune. As shown through statistical arguments in that paper, the presence of 300-3000 1000- km diameter and larger objects in the Uranus-Neptune zone makes the Uranus Neptune tilting, Triton's capture, and the formation of the Pluto- Charon binary each likely. Stern (1991) also showed that the vast majority of these ice dwarfs were scattered (with the comets) to the Oort Cloud and Kuiper Belt by strong perturbations from Neptune and Uranus. Pluto- Charon and Triton remain in the 20-30 AU zone today, only because they are trapped in unique dynamical niches which protect them against loss to strong perturbations. This hypothesis implies that Pluto and Triton are important `relics' of a very large population of icy bodies, which by number (but not by mass) dominate the planetary population of the Solar System. As such, these interesting bodies no longer appear to be isolated anomalies in the architecture of the outer Solar System, but are instead seen to be genetic relations from a heterogeneous ensemble of precursor objects that were previously not recognized as a large class unto themselves.

4.11. IMPLICATIONS FOR THE FORMATION OF THE SOLAR SYSTEM

The Pluto Charon system lies on the inner edge of the Kuiper Belt, and in consequence represents the largest and best-studied examples of solid material out of which the giant planets were formed. It has become increasingly likely, based on astronomical studies of other disks in star-forming regions, as well as spacecraft and Earth-based study of our own Solar System, that proto-planetary disks are both pervasive and chemically complex (Figure 6). Pluto and Charon reside in a region of Solar System corresponding to that part of the protoplanetary disk in which infalling primitive grains were only partially heated and altered, and where nebular gas likely retained a strong signature of interstellar composition. These assertions are exciting in that they argue for a strong link with the original, nascent molecular cloud.

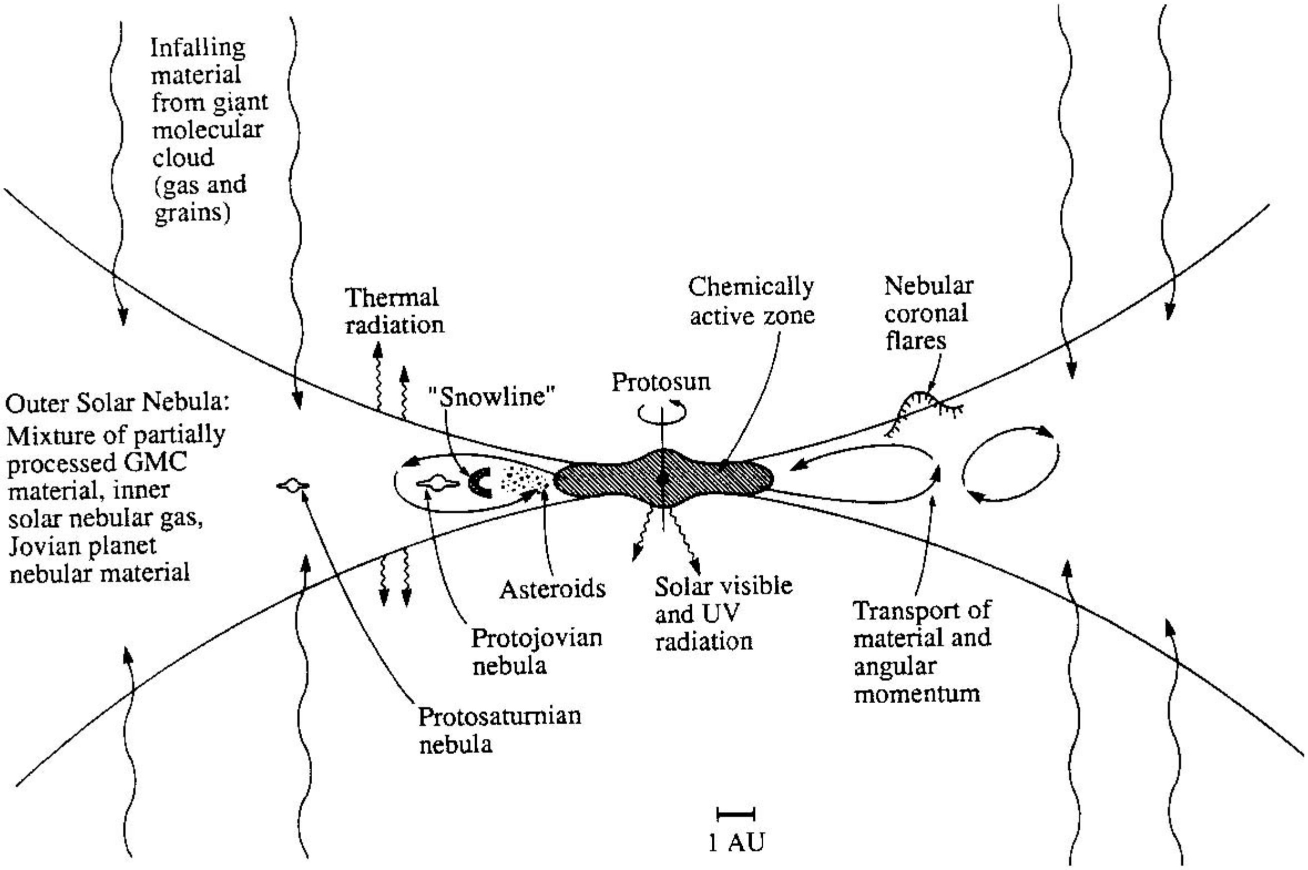

Figure 6. Schematic of selected physical and chemical processes in the precursor of our Solar System, the so-called solar nebula. From Lunine 1989.

The important dynamical relationship established between Kuiper Belt objects, short period comets and Pluto Charon enables the possibility of studying material over a range of sizes from a common region of the protoplanetary disk. Size is an important indicator of the amount of post-formation processing of material. Interestingly, although Pluto may be evolved relative to the smaller Kuiper Belt and cometary objects, its size has also allowed volatiles from its interior to be outgassed to the surface, where they are accessible to observation. We do not know whether smaller Kuiper Belt objects have exposed volatiles.

Detailed study of the full range of objects from Pluto down through short period comets will constrain composition and history of this material, which represents primitive icy material in much the same way that the carbonaceous chondrites are samples of primitive rocky and refractory- organic material. In particular, it may be possible to constrain the amount of radial mixing of solid and gaseous volatiles from the outer to inner solar nebula by detailed analysis of such material (Lunine et al., 1991; 1995). This, in turn, represents a primary chemical constraint on mechanisms of angular momentum and energy transport through the nebula, a key issue in understanding how proto-planetary disks work (Cassen, 1995). Relating the composition of the ices on Pluto, Kuiper Belt and short-period cometary bodies to measurements in the Jovian atmosphere and Titan's atmosphere by Cassini and Galileo will allow construction of a history of the volatile molecular species from infall into the disk through the early history of planet formation.

5. Spacecraft History and Approach

5.1. INTRODUCTION TO SCIENCECRAFT

In order to achieve its ambitious goals for performance, flight time, and cost, a new approach is needed for a mission to Pluto. The highly constrained environment requires that maximum effort be placed upon the sharing of scarce spacecraft resources and that new technologies be used where ever possible to lower power, mass, and cost. The sharing of resources requires the reduction or removal of the usual barriers between spacecraft subsystems, between different science instruments, and between the science instruments and the spacecraft. The construction of such a highly integrated system requires that new emphasis be placed on measurement objectives. The science instruments and spacecraft must be designed to carry out a specific set of well-defined measurements. The capable and general purpose spacecraft and modular set of science instruments flown on earlier missions can no longer be afforded; rather the spacecraft and instruments must be designed to carry out a specific set of tasks and to achieve those tasks in the most efficient manner possible. Removal of the usual compartmentalization in spacecraft and instrument design requires a high degree of communication between the designers of the various parts of the spacecraft and the instruments. In this approach the usual dividing line between spacecraft and science instruments becomes blurred. In recognition of this and the fact that the spacecraft is a vehicle designed to carry out scientific measurements, the flight system is referred to as a “Sciencecraft.”

Essential to the Sciencecraft concept is development of a well-defined, specific set of measurements very early in the spacecraft design process. A well defined mission sequence is also necessary so that the relative timing of the observations can be determined. The measurement timeline drives the instrument design. For example, the focal lengths of various cameras can be chosen in a manner which achieves the required spatial resolution but with an understanding of the implications of the entire suite of measurements on the power, data rates, and pointing requirements placed on the spacecraft. This approach is essentially the inverse of the customary approach where the spacecraft and each of many instruments are designed separately and decisions about specific measurements are made after spacecraft construction, in fact usually after spacecraft launch. With the Sciencecraft approach the requirements for power, thermal loading, data rates, spacecraft stability, etc. can be calculated with high accuracy leading to a more efficient use of spacecraft resources. All major conflicts regarding use of spacecraft resources (power, data rates, pointing capabilities, etc.) must be recognized and settled in the design phase of the mission.

The goals outlined above can only be achieved through a high degree of cooperation between spacecraft and instrument designers. Instrument designers must have an understanding of the spacecraft and the ability to make sugggestions to spacecraft designers and the spacecraft designers must have the same priviledges with the science instruments. For this reason it is essential that the science team be chosen much earlier in the design phase than is usual and it is a necessary consequence that the spacecraft and mission design will be relatively immature at the time that the science instrument package is chosen.

This approach to spacecraft design was developed by a small group of scientists and engineers led by L.A. Soderblom of the U.S. Geological Survey and including P. M. Beauchamp (JPL), R.H. Brown (JPL), D.H. Rodgers (JPL), G. Vane (JPL), R.V. Yelle (Boston University), D. Huxtable (Olin Aerospace), C. Meserole (Boeing Corp.), and D. Wang (System Sensors Group). The Sciencecraft approach was first illustrated in developing a mission concept called “Kuiper Express” to examine the feasibility of an economical mission to the remote Kuiper Belt (Dyson, 1995). Obviously, a mission to Pluto has strong similarities to a mission to the Kuiper Belt. The “Pluto Express” borrows heavily from the approach and many of the ideas generated by the Kuiper Express study.

5.2. IMPLEMENTATION OF THE SCIENCECRAFT PHILOSOPHY ON PLUTO EXPRESS

Having an integrated sciencecraft implementation team, a co-located design center with concurrent engineering tools, and a spacecraft development testbed are key elements being used by the Pluto Team to lower the development and operations costs of both hardware and software.

Mission system design, which includes sciencecraft engineering, science, software, mission design, and mission operations, is being developed in a Project Design Center (PDC) which has state of the art computer aided tools. Design, optimization, and costing of all the mission system elements will take place concurrently using the tools available in the PDC. All of the different mission system disciplines work together as a team in one large room during sessions in the PDC. Each discipline has one or more computer workstations which are all linked together to enable transfer and sharing of data. Individual monitors can be projected onto large display screens to facilitate the team working together on a design problem.

Software for the Pluto program is being developed in a co-located interactive Flight System Testbed (FST) environment, a process which has already begun. Early work is being done through software simulations of the various sciencecraft subsystems, but actual hardware elements are being plugged in as brassboard and prototype hardware becomes available. As software blocks are written, they are proved in the testbed, and anomalies can be intentionally inserted to test fault protection features and find bugs. The testbed is used eliminate problems in both software and hardware interfaces early in the program. It is anticipated that by the time the flight sciencecraft begins assembly, a complete set of flight software will be up and running in the testbed using prototype hardware.

Although it is highly desired that the science team members be physically co-located with the Pluto Express Team for all phases of the project, there are some workstation based videoconferencing tools being brought on line in both the PDC and the FST to facilitate “virtual co-location”. If this proves to be effective, it will allow some members of the science team to be physically away from the Pluto Team for much of the time, while still enabling them to participate fully in all of the design, simulation, testing, optimization, and costing sessions.

It must be emphasized that the sciencecraft design described here is only an example of what the final optimized sciencecraft design might look like. After the science team is selected and brought on board, a drastically different architecture might be worked out in the PDC and FST sessions with the full team (including science) assembled.

5.3. RESOURCES FOR THE SCIENCE INVESTIGATIONS

As part of the strawman sciencecraft design an allocation of resources was made for a science payload. It is expected that this payload would be developed as a fully integrated component of the sciencecraft and not as a more traditional add-on subsystem. But to set a benchmark to which design alternatives may be compared, mass and power estimates for the strawman science payload are 7 kilograms and 6 watts of power, including the radio occultation ultra stable oscillator. A full description of the strawman payload and its focused science objectives are given in the next section.

6. Mission Goals

6.1. SCIENCE OBJECTIVES

The Outer Planets Science Working Group carefully considered the range of science objectives appropriate to a first reconnaissance mission to Pluto. These were then prioritized and their final ranking, endorsed by the Solar System Exploration Subcommittee, appears below. Category 1a objectives are considered absolutely essential to the first-scientific reconnaissance mission; Category 1b are considered important but not mandatory; Category 1c are considered desirable but secondary. A larger list of other objectives was given an even lower priority as Category 2. That list is not provided here but is available from NASA Headquarters in documents of the OP- SWG activities.

The categorization resulted in a scientifically compelling set of focussed goals for a first reconnaissance:

6.1.1. *Category 1a*

- Characterize global geology and morphology of Pluto and Charon;
- Surface composition mapping;
- Characterize the neutral atmosphere and its escape rate.

6.1.2. *Category 1b*

- Surface and atmosphere time variability;
- Stereo imaging;
- High resolution terminator mapping;
- Selected high resolution surface composition mapping;
- Characterize Pluto's ionosphere and solar wind interaction;
- Search for neutral species including H; H_2; HCN; C_xH_y , and other hydrocarbons and nitriles in Pluto's upper atmosphere. Obtain isotopic discrimination where possible;

- Search for an atmosphere around Charon;
- Determine bolometric bond albedos;
- Surface temperature mapping.

6.1.3. Category 1c

- Characterize the energetic particle environment;
- Refinement of bulk parameters (radii, masses, densities) and orbit;
- Magnetic field search;
- Additional satellite and ring searches.

6.2. MEASUREMENT OBJECTIVES AND GOALS

In this section we list, by science area, measurement objectives for instruments, or in cases where appropriate, the slightly looser “goals” for instrument capability. These measurement objectives and goals permit the mission to meet the Category 1a science objectives given above; some payloads may also meet other objectives in Categories 1b and 1c.

Coverage objectives assume a two spacecraft mission.

6.2.1. Geology and geomorphology

Monochromatic mapping: Obtain monochromatic global coverage of both Pluto and Charon at a resolution of 1 kilometer per line pair (1 km/lp), or equivalent. The 1 km/lp objective is to be obtained at the subspacecraft point in each image; it is understood that a combination of image projection effects and spacecraft data storage limitations may degrade resolution away from the subspacecraft point.

Color mapping: Obtain global coverage of both Pluto and Charon in 3 to 5 color bands at a resolution of 3-10 km/lp (or equivalent). The resolution requirement is to be obtained at the subspacecraft point in each image; it is understood that a combination of image projection effects and spacecraft data storage limitations may degrade resolution away from the subspacecraft point.

Phase angle coverage: Obtain sufficient imaging at moderate and high phase angles to specify the phase integrals of Pluto and Charon.

Image dynamic range and signal-to-noise ratio (S/N): For all imaging, provide sufficient dynamic range to cover brightness contrasts of up to 30 (i.e., normal albedo between 0.03 and 1) with an average S/N goal of ~ 100, but somewhat lower S N in the darkest regions.

6.2.2. *Surface composition mapping*

Mapping coverage, resolution and sensitivity: Obtain infrared spectroscopic maps of at least one hemisphere of both Pluto and Charon with approximately 10 km pixel resolution at disk center. Global coverage may be possible with two spacecraft. Be able to detect a < 0.02 change in albedo everywhere in the spectrum.

Spectral coverage and resolution: For each spatial resolution element, obtain a spectral resolution ($\lambda/\Delta\lambda$) of at least 250 per pixel over all or part of the 1-5 micron region (or beyond, if relevant).

Goal for compositional determination: Using the techniques of quantitative near-infrared spectroscopy, determine the spatial distribution and crystalline phases (i.e., α or β) of frozen N_2 and secondary constituents such as *CO*; CH_4. Determine quantitatively the presence of such additional major exposed volatiles, hydrocarbons, and minerals (or rocks) as may exist, all at the spatial resolution of 5-10 km pixel or equivalent.

6.2.3. Neutral atmosphere characterization

Composition: Determine the mole fractions of N_2; CO; CH_4 and Ar in Pluto's atmosphere to at least the 1% level. Abundance of any constituents below this level (minor constituents) is a Category 1b science objective.
Thermospheric thermal structure: Measure T and dT/dz at 100 km vertical resolution to 10% accuracy at gas densities of 109cm-3 and higher.
Aerosols: Characterize the optical depth and distribution of near-surface haze layers over Pluto's limb at a vertical resolution of 5 km or better.
Lower atmospheric thermal structure: Measure T and P at the base of the atmosphere to accuracies of ±1 K and 0.1 μbar.
Evolution: Determine the atmospheric escape rate.

6.3. STRAWMAN PAYLOAD

The strawman payload developed by the Outer Planets Science Working Group is designed conceptually to meet all of the Category 1a science objectives. It is comprised of an integrated ultraviolet, visible, and infrared remote sensing package, plus a radio science experiment. In the strawman, neither the technique nor the architecture of the integrated package is described; all that is provided is a guide to how the investigation could respond to the science objectives through the use of instruments with particular choices of wavelength range, sensitivity and resolution (spatial and spectral). We discuss the radio investigation in more detail because of its intimate and potentially complex relationship to the sciencecraft communication subsystem.

6.3.1. *Visible imaging*

The Pluto Express visible wavelength images of Pluto and Charon will permit geological mapping of surfaces and will contain important insights into the formation, evolution, and composition of the system. Surface albedo variations which are seen in ground data and Hubble images will be resolved into regions of differing terrain or composition. Images of Pluto will likely reveal deposits of ice which will help to understand the atmosphere and its interaction with the surface during its seasonal cycle of sublimation and condensation. Cratered areas will provide insight into the impactor flux at the edge of the Kuiper Belt, as well as provide relative ages of surfaces. Large scale morphologic features will inform us of the thermal and geologic history of Pluto's crust.

Two categories of images of Pluto and Charon form the primary data set required to support the science objectives. These are 1) multispectral images with 5-10 km resolution in several (i.e., two to five) wavelength bands chosen to provide compositional information and 2) full-disk high-resolution monochromatic image (1 km lp at sub-spacecraft point) to provide information on surface structures.

Other image data that can be obtained by the visible imager, contingent on the design, are 1) images of selected surface regions at higher resolutions, 2) observations of atmospheric aerosols in forward scattered light, 3) data taken over a range of phase angles, 4) selected stereo pairs and 5) images of the space surrounding Pluto to search for small satellites.

6.3.2. *Infrared Mapping Spectroscopy*

The Infrared Spectral Mapping Component would determine the surface compositions of Pluto and Charon by performing spectroscopic mapping in the near- infrared part of the spectrum, the wavelength range chosen to capture key spectral features (and hence make quantitative measurements) of exposed volatiles, hydrocarbons, and minerals. On approach, maps of the sunlit sides of both Pluto and Charon would be recorded at high spatial resolution. The spectral resolution ($\lambda/\Delta\lambda$) is ~ 200 per pixel. The imaging format will permit full disk mapping with spatial resolution better than 10 km per pixel.

6.3.3. *Ultraviolet Spectroscopy*

The goal of this component is to measure the composition and structure of the neutral atmosphere by studying Pluto's airglow and detecting spectral absorption features during solar occultation; the general wavelength region of interest is 50-200 nm. This portion of the remote sensing investigation would be designed to meet the neutral atmosphere structure and composition objectives except for measurement of temperature and pressure near the surface. Sufficient sensitivity, spectral resolution, and spectral coverage are required to measure the mole fractions of N_2; CO; CH_4, a vertical resolution of 100 km to a 10% accuracy for atmospheric densities exceeding $10^9 cm^{-3}$.

6.3.4. *Radio Science Investigation*

The Radio Science occultation will measure the vertical structure of Pluto's atmosphere by sensing the phase retardation of the radio signals imposed by the neutral gas during Earth occultation immersion and emersion. This experiment is expected to meet the neutral atmosphere objective of determining the surface temperature and pressure. In addition, the atmospheric structure for several scale heights above the surface will be determined so that a broad picture of the factors and processes controlling the atmosphere in the vicinity of the Pluto's surface can be developed.

Estimates of the surface pressure of Pluto range between roughly 3 and 50 (μbars), but the uncertainties are essentially unknown. Consequently, it is prudent to consider the lower value as an upper bound for the design of any occultation observation. Meaningful measurements will require sensitivities adequate to characterize accurately an atmosphere in the range of 1 μbar. One approach to estimation of the expected effects is to scale observed values from the Voyager Triton occultation to the Pluto case. This results in an expected observable phase shift of a surface occultation ray at Pluto in the range of 0.12 radians/μbar . From these considerations it is clear that stable measurements of phase with accuracies in the range of 0.01 radian (0.5 degrees) will be required. From these considerations the radio occultation should yield the atmospheric structure for pressures greater than about 1 μbar. In particular, for the nominal surface pressure of 3 μbar the temperature and pressure both should be obtained to a few percent. The observations should provide adequate signal-to-noise ratio to support the objectives, and a sufficient sampling rate to determine the position of the surface to within approximately 100 m radius relative to solution atmospheric profile and the navigation trajectory solution.

As a Category 1b objective, the ionosphere of Pluto also would be sensed by the same experiment; measurements should begin above the highest expected ionosphere to avoid contamination of the neutral atmospheric data by uncalibrated ionospheric effects, and to obtain the ionospheric profile. While the neutral atmosphere of Charon is not thought to be sensible by radio occultation, a possible ionosphere of Charon is also of interest and should be accessible to radio occultation observations.

Separate occultations are possible with two spacecraft on different trajectories, or it may be possible to accomplish a near occultation of either Pluto or Charon, followed by a distant occultation of the other. In either event the occultations are expected to be rapid, with vertical component of the ray path velocity in the range of 3.5 km/sec as determined by the characteristics of flight times. While conditions will be somewhat different for different trajectory options there will be essentially no opportunity to adjust the trajectory for occultation purposes other than by choice of the asymptotic aim point.

The Pluto Express communications system is planned to operate uplink at X-band (7.1 GHz), and downlink at Ka-Band (32 GHz). While some change may be expected as the sciencecraft design process advances, the spacecraft antenna is expected to be approximately 1.5 m diameter, and the downlink transmitter power will be in the range of 1 w. The spacecraft will be commanded through NASA Deep Space Network facilities, nominally radiating 20 kW with 34 m diameter ground antennas. It is an open question as to whether the onboard system will be a conventional, coherent transponder, such as have been flown on past missions, or a transceiver with a non-coherent data transmission system. In the first instance the radio system would be capable of deriving its downlink signal either from an onboard oscillator or from the uplink signal, when present. There would be no mission engineering requirement to carry a stable frequency reference, although it is planned that the radio design would permit use of such a device were it to be required by a radio science investigation. In the second instance all downlink transmissions would be derived from onboard oscillators, and a stable frequency reference such as the “ultra-stable” crystal oscillators (USOs) carried by Voyager and Galileo would be required for spacecraft navigation. This equipment will be available for a radio science experiment implementation, but any additional system elements required must be supplied as part of the scientific investigation development. Use of the the spacecraft transmitter as a signal source “as is” with reception on the ground would result in an unacceptably low signal-to-noise ratio for the Pluto atmospheric objectives.

The investigation design goal is to integrate as much of the experiment as possible with the spacecraft telecommunications system in order to improve total mass, power, operability, and cost of the spacecraft and instrument, while maintaining the investigation's capability to address the science objectives.

6.3.5. *Particles and Fields*

There is no particles/fields instrument integrated package per se included in the strawman payload developed by the Outer Planets Science Working Group or the Science Definition Team. Many of the particles and fields science objective require in situ measurements. An opportunity for enhancing the payload to accomplish these additional objectives is outlined in the section on international collaborative options.

7. Baseline Mission and Spacecraft Capabilities

7.1. BASELINE MISSION

The reference mission plan envisions the launch of two Pluto sciencecraft on separate launch vehicles augmented by an existing solid rocket motor upper stage, on Jupiter gravity assist (JGA) trajectories. A Jupiter flyby distance of 5.5 RJ gives a flight time to Pluto of about 10 years for launches in 2003 (Figure 7). This is faster than the 12-year Voyager transit to Neptune and Triton. The approach speed at Pluto will be 12-18 km/sec, which is similar to Voyager flyby speeds at Titan and Triton.

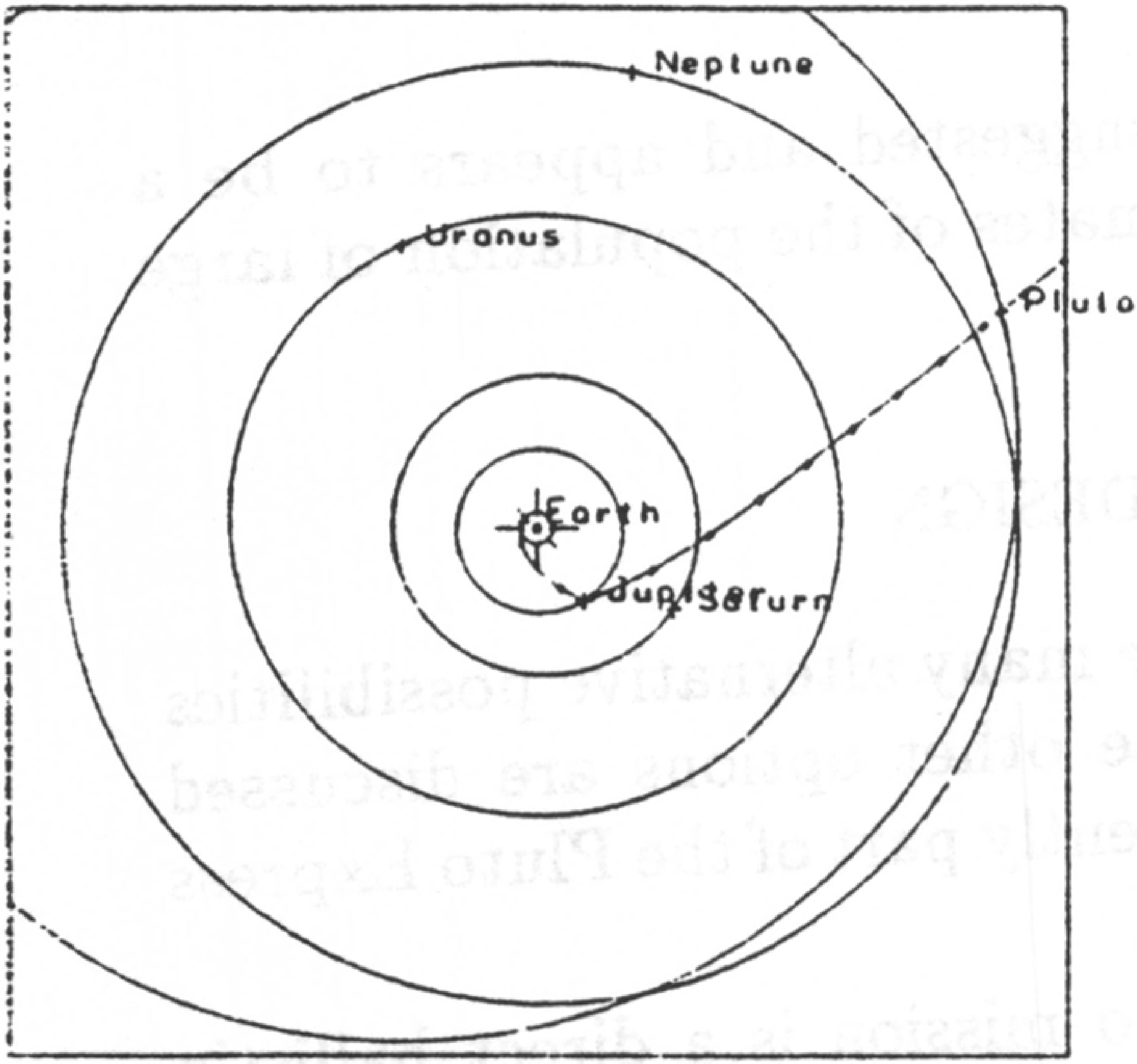

Figure 7. Example of a Pluto Express trajectory, with Jupiter gravity assist, for a launch in 2003

The reference Pluto Express mission plan involves two sciencecraft for several reasons. These include the reduced risk of a malfunction fatal to the mission, and the significantly improved science return, particularly to accomplish complete mapping of Pluto and Charon.

Distant remote sensing observations of the Pluto-Charon system will begin some 3 months prior to closest approach. This is when imaging resolution exceeds that of the repaired Hubble Space Telescope (HST). Over a timebase of 20-35 rotations, Pluto and Charon will be observed at increasing resolution, and a search will be made for faint satellites. Also during distant approach, UV spectrometer observations will search for an H/H_2 corona around Pluto. In the days leading to closest approach, IR surface mapping and UV airglow studies will become a priority.

The reference flyby design brings the first sciencecraft to a distance of about 15,000 km from Pluto, and permits both Earth and solar occultations. This trajectory places the first sciencecraft at least 3 times closer to Pluto than Voyager came to Triton. Post- flyby studies would include high phase angle mapping, searches for orbiting dust structures, and nightside UV spectroscopy.

Since two sciencecraft are launched, their encounter trajectories will be separately optimized. In order to complete the 1-km global mapping requirement, the second sciencecraft will be targeted to arrive over the opposite hemispheres of Pluto and Charon. It is expected that the two flybys will be separated by about 6 months. This will allow the data from the first encounter to be sent down and analyzed to optimize the science return from the second. It also may provide a substantial timebase of observations to detect atmospheric decay and surface volatile transport. The second encounter could feature an approach within 2000-3000 km of Pluto, Charon radio solar occultations, or other objectives. After the two spacecraft leave the Pluto-Charon system, they will be traveling in the direction of the heliopause's closest point to the sun, at 3 AU yr. Extending the mission to fly by a Kuiper disk object has been suggested and appears to be a reasonable possibility based on current estimates of the population of large objects.

7.2. OTHER OPTIONS FOR THE MISSION DESIGN

Besides the baseline mission design, there are many alternative possibilities for delivering a sciencecraft to Pluto. These other options are discussed below to provide an overview but are not currently part of the Pluto Express reference mission design.

One preferred flight path for a fast Pluto mission is a direct ballistic trajectory. This results in a relatively benign radiation environment, and allows for very low cost mission operations since no gravity assist flybys and few maneuvers are entailed. Additionally, launch windows for direct trajectories exist once a year and do not significantly change. However, for flight times under ten years this requires Titan IV Centaur or Proton class launch vehicles with at least one additional upper stage such as a typical satellite perigee raise motor. Unfortunately, big rockets and upper stages are not cheap, but perhaps might be available in conjunction with a US Russian partnership on the mission.

In order to allow for lower cost missions on smaller launchers without the expense of an upper stage, there are other mission design options. Earth Jupiter gravity assist trajectories can achieve flight times of around ten years, but require the spacecraft to be capable of surviving significantly higher radiation levels, and require a much larger onboard propulsion system. The reference straight Jupiter Gravity Assist (JGA) trajectory is available for Delta, Atlas, and Russian Molniya class launchers, but an additional upper stage and its attendant cost is required.

There is also an option for a Venus Venus Venus Jupiter Gravity Assist (VVVJGA) trajectory which avoids an Earth flyby and can be launched on a Delta or Molniya class vehicle without an upper stage, with a flight time of 12.2 years. Solar Electric Propulsion (SEP) might also be an attractive option for getting to Pluto in about ten years on a Delta class vehicle, but this technology must first be developed to a point where it can be purchased, integrated to the spacecraft and operated at an affordable cost.

Several trajectories and launch vehicle options continue to be studied with particular emphasis on lower cost Delta and Molniya class launchers. These provide a good balance between economy and performance while still allowing flight times of about ten years by using a Jupiter gravity assist. Both launchers also allow the possibility of carrying two sciencecraft aboard one launcher. If budgets are further constrained, this would save the cost of the second launcher and still enable a two sciencecraft mission while increasing the risk of losing both sciencecraft. However, due to the high reliability of these vehicles and the decade long flight time, this dual sciencecraft option is highly preferred over a scaled-back mission of having only a single sciencecraft on a single launcher.

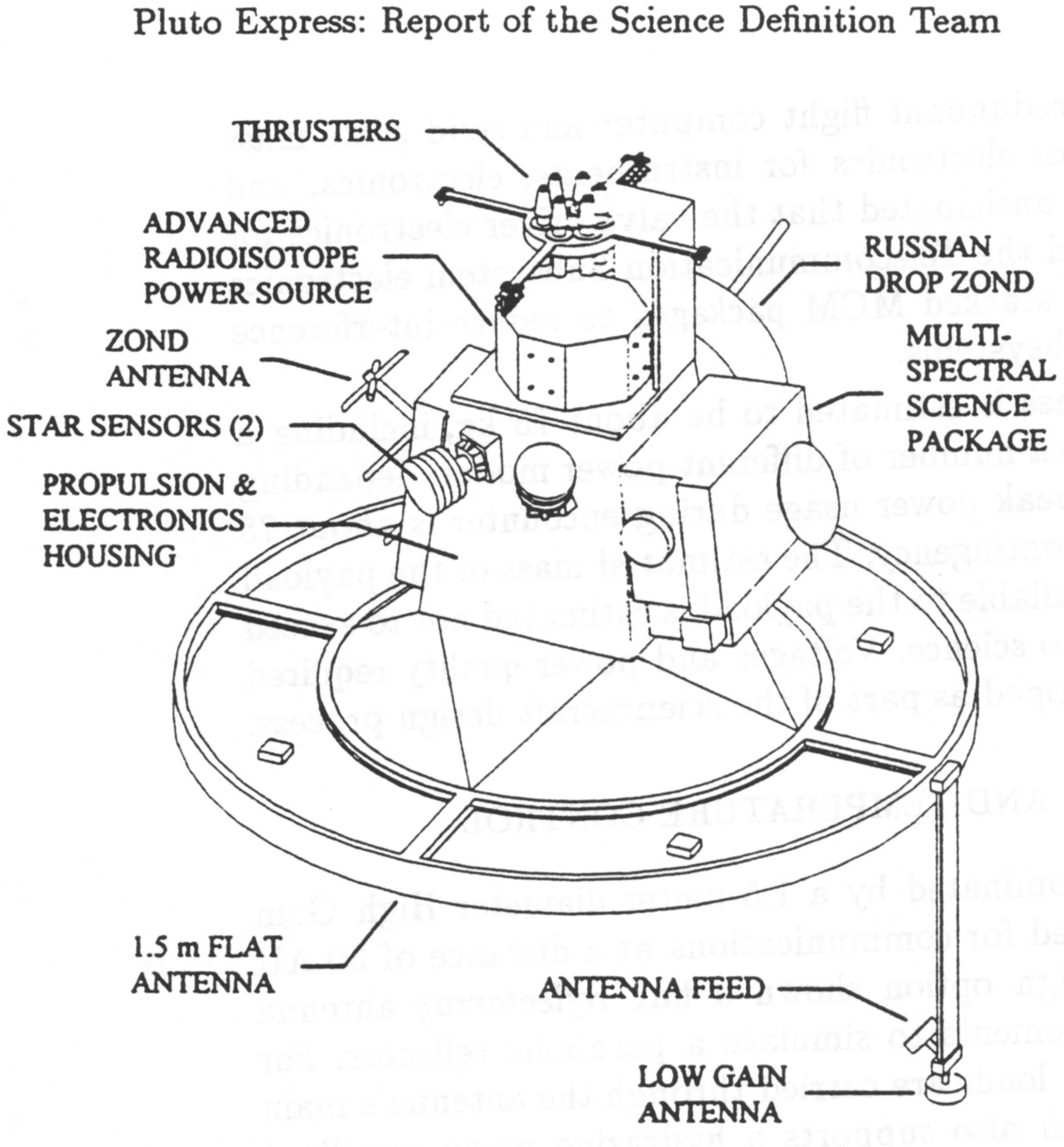

Figure 8. Pluto Express sciencecraft.

7.3. SYSTEM DESIGN

The sciencecraft flight system consists of hardware and software. The major hardware elements are depicted in Figure 8. Sciencecraft components are classified into three major groups: sensors, electronics, and motive effectors. These elements are integrated together inside a structural and thermal enclosure. Additionally, a power source provides electrical and thermal energy to the sciencecraft system.

It is planned that most of the electronic components will be integrated into a three dimensional stack of Multi-Chip Modules (MCM's) to greatly reduce the volume, mass, and the amount of cabling required. The small size also significantly reduces the mass of any additional radiation shielding required. This MCM stack will consist of the Sciencecraft Data Subsystem (SDS) with its block redundant flight computer and solid state mass memory, and power control electronics for instruments, electronics, and pyrotechnic initiators. It is anticipated that the valve driver electronics for the propulsive thrusters and the Telecommunication Subsystem electronics will be housed in separate stacked MCM packages to reduce interference problems with the other subsystems.

The sciencecraft dry mass is estimated to be about 75 kg, including a 15% contingency. There are a number of different power modes, depending on mission phase, but the peak power usage during encounter is about 75 watts, including a 15 watt contingency. The estimated mass of the payload is 7 kg or less. The power available to the payload is estimated not to exceed 6 watts peak, including radio science. Voltages and power quality required by the payload will be developed as part of the sciencecraft design process.

7.4. MECHANICAL DESIGN AND TEMPERATURE CONTROL

The sciencecraft design is dominated by a 1.5 meter diameter High Gain Antenna (HGA) which is used for communications at a distance of 30 AU from the Earth. In the design option shown a flat *reflectarray* antenna uses thousands of printed elements to simulate a parabolic reflector. For this particular design, launch loads are carried through the antenna's main structural support ring which also supports a hydrazine monopropellant tank through a graphite conical shell structure on the back.

Surrounding the hydrazine tank is a modular bus structure comprised of four trapezoidal panels fabricated from a graphitic composite material. One of the panels supports valves, regulators, and other propulsion components. Another panel is used to mount the science package on the exterior. The interior of the other two panels support telecommunication components, gyros, and the integrated MCM microelectronics package, while the exterior surfaces support temperature control louvers, a probe relay antenna and receiver, and star sensors.

A 100 watt (at beginning of mission) electric Radioisotope Power Source (RPS) is mounted to the top of the bus structure so that some of its 500 watts of thermal output can be used to warm critical elements inside the bus such as propulsion components, the hydrazine tank, and electronics. Also mounted to the top of the bus is a bracket which goes around one side of the RPS to support attitude control and Trajectory Correction Maneuver (TCM) thrusters at a location which provides ample heat from the RPS and also minimizes thruster plume impingement interactions with the antenna and other sciencecraft elements.

Figure 9 illustrates the thermal design of the vehicle. Radiated heat from the RPS is directed and controlled by Multi-Layer Insulation (MLI) blankets and louvers to create several thermal zones.

Analysis indicates that this design can maintain temperatures within specification with little or no use of electrical heaters, over a range of 1 to 30 AU from the sun.

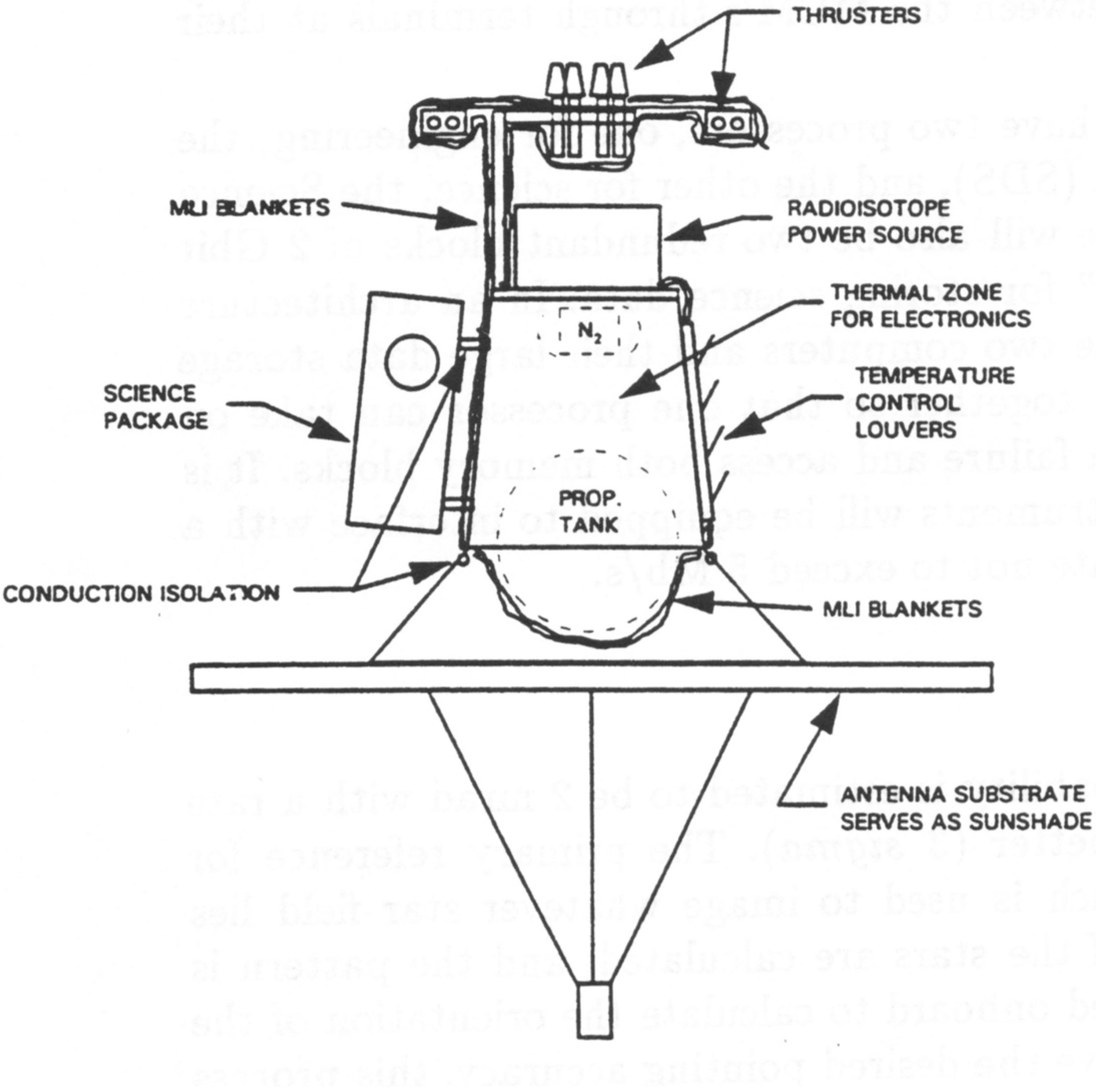

Figure 9. Pluto Express sciencecraft thermal design.

This represents a factor of 1,000 difference in solar illumination. The payload thermal environment at Pluto is such that the estimated temperature of a component thermally isolated from the sciencecraft will be in the range 120 - 150 K. Components requiring a higher temperature should be thermally connected to the spacecraft. Components requiring a lower temperature, such as the infrared detectors, will need to supply an additional means of cooling.

7.5. SPACECRAFT DATA SUBSYSTEM

The sciencecraft avionics consist of a number of standardized MCM's which will be integrated together in a three dimensional stack. This modular stacking greatly decreases the volume and mass of electronics and reduces the mass of cabling and connectors. Significant progress has been made by JPL personnel Leon Alkalai, Tom Borden, and others in this development, and a prototype MCM for the Advanced Flight Computer has already been produced. Signals are carried between the MCM's through terminals at their perimeter.

The flight computer will have two processors, one for engineering, the Sciencecraft Data Subsystem (SDS), and the other for science, the Science Data Processor (SDP). There will also be two redundant blocks of 2 Gbit DRAM “solid state recorder” for storing science data. In an architecture developed by Savio Chau, the two computers and their large data storage memories are cross strapped together so that one processor can take on all functions in the event of a failure and access both memory blocks. It is assumed that the science instruments will be equipped to interface with a serial digital I/O port at a rate not to exceed 5 Mb/s.

7.6. ATTITUDE CONTROL

Attitude control pointing capability is estimated to be 2 mrad with a rate control of 10 μrad/sec or better (3 sigma). The primary reference for pointing is a star sensor which is used to image whatever star field lies in its view area. Centroids of the stars are calculated, and the pattern is compared to a star map stored onboard to calculate the orientation of the sciencecraft. In order to achieve the desired pointing accuracy, this process will take place about every second.

During Trajectory Correction Maneuvers (TCM's) or during some emergency scenarios, the attitude reference is taken over by an Inertial Reference Unit with a bias instability of about 1 degree per hour (3 sigma). Sun sensors are included on the sciencecraft to help with initial attitude acquisition following launch, and for certain emergency scenarios.

7.7. TELECOMMUNICATIONS

The Pluto Express project plans to utilize the advanced technology Small Deep Space Transponder (SDST) for communications with the Earth. This unit employs Monolithic Microwave Integrated Circuits (MMIC's) implemented on MCM's at very small mass and volume. The output of the SDST will feed GaAs PHEMT Ka-band Solid State Power Amplifiers (SSPA's). Uplink is X-band at 7.1 GHz, and downlink is Ka-band at 32 Ghz.

A 1.5 m diameter High Gain Antenna (HGA) provides a data rate of between 150 and 450 bits sec at Pluto, depending on the DSN ground antenna station configuration used. A Low Gain Antenna (LGA) is included to allow communications early in the mission in situations where the HGA is not pointed directly at Earth. This is useful for initial acquisition after launch, and for certain emergency scenarios. After the flight system passes Mars' orbit, the LGA will no longer be able to provide a data link, and the operations must depend on the HGA.

7.8. POWER

While several power source options are being evaluated, a Radioisotope Power Source (RPS) (using heat from radioactive decay to generate electricity) looks like the most robust technology available today for providing reliable power at edge of the Solar System and out into interstellar space. Radioisotope generator technology used for Galileo, Ulysses, and Cassini is usable for a Pluto mission at about a 6% conversion efficiency, but more advanced converter technologies are being explored to increase the efficiency of these devices up to about 20%. This increased efficiency combined with lower power consumption would enable the Pluto sciencecraft to fly a much lighter power source with about 25 times less radioisotope material than Cassini. The advanced RPS designs being studied would use two General Purpose Heat Sources (GPHS's), out of the 18 left over from the Cassini Program, put into an advanced converter. It is estimated that the RPS would supply 98 watts at the beginning of mission and less than 87 watts at one year after the Pluto encounter.

7.9. PROPULSION

To achieve fine pointing control of a low mass flight system with very small moments of inertia, it is necessary to have extremely low impulse thrusters with a small moment arm so that the vehicle is not overly torqued when they fire. Long life dry nitrogen cold gas thrusters that provide a force of only 0.0045 N are currently being developed for the Pluto mission. The total amount of gas required for providing attitude control over the ten year mission is less than 1 kg. For Trajectory Correction Maneuvers (TCM's), three 5 N monopropellant hydrazine thrusters will be used. The high pressure nitrogen tank which feeds the cold gas attitude thrusters is also used to pressurize the hydrazine tank that feeds the TCM thrusters.

8. Extended mission to the Kuiper Belt

The recent discovery of the Kuiper Belt and information about the number and distribution of bodies in it made it desirable to determine whether the Pluto Express mission could also explore this region of the Solar System, after the Pluto encounters. The scientific motivation for Kuiper Belt object flybys include:

- *The opportunity to explore a wholly new region of the planetary system;*
- *the mounting evidence that the Kuiper Belt is a region where planet- building processes were arrested in mid-stride;*
- *the possibility that short-period comets originate from this belt;*
- *the emerging evidence that Pluto is in fact itself a Kuiper Belt object.*
-

With these compelling motivations in mind, the Pluto Express project and SDT have evaluated the feasibility and merit of sending the Pluto Express spacecraft on to fly by one or more Kuiper Belt objects.

From a feasibility standpoint, the Pluto Express sciencecraft seems well- suited to conducting additional flybys and returning data from these encounters to Earth, at least out to distances of 45-50 AU. A mission analysis shows that with ~ 4 $\times 10^4$ 100-400 km (“intermediate-sized”) objects and perhaps 6 - 10 $\times$ 10^9 comets in the Belt at distances of 50 AU or less (extrapolated from observations which currently cover a narrow portion of the sky), it is quite likely that one or both Pluto Express spacecraft can be retargeted for close encounters of Kuiper Belt objects. For example, to reach one of the 100-km diameter-class objects detected from ground-based telescopes, statistics show that the spacecraft trajectory must only be turned ≈ 0.5 deg, on average; this will require a 50-80 m/s ΔV maneuver after the Pluto encounter. Since the Pluto Express spacecaft is expected to carry 320 m/s of ΔV capability at launch, it is not unlikely that 50-80 m s of capability will still be available after the Pluto encounter. Reaching a comet-sized object in the Kuiper Belt will be easier in the sense that the comets are ~ 10^5 times more numerous than the intermediate-sized objects, and therefore about ~60 times more closely spaced. However, it will be more difficult to determine the orbit of such a small body beforehand. The actual selection of specific targets need not be made until well into the mission, depending upon requirements for the precision of the orbit determination.

The scientific potential of a flyby with the Pluto Express sciencecraft is high. In fact, the IA payload already-specified for Pluto exploration is nearly ideally suited to the flyby reconnaissance of the icy bodies that lie beyond Pluto in the Kuiper Belt. With its high resolution imager, its IR spectral mapper, and (to a lesser extent) its UV spectrometer, a highly valuable dataset could be obtained. For example, maps could be obtained from many tens of thousands of km range with a resolution of a few km or better, which would provide shape, geology, and color unit maps with 10^4 resolution elements or more on the surface of a 100-km sized object. The SDT believes that the Kuiper Belt mission extension would be scientifically compelling, publically exciting, and unquestionably historic. In this context, we note that the Pluto Express mission represents the only mission expected to reach this distant region of the Solar System in the next 15 years or more. The SDT strongly recommends that nothing be done during mission development to preclude the possibility of the Kuiper Belt mission extension, and encourages NASA to consider whether a Kuiper Belt flyby should be elevated to a primary mission goal.

9. Options for International Cooperation

9.1. DROP ZONDS

In early 1994, US-Russian contacts identified the possibility that a joint US Russian Pluto mission would be of interest to both national space programs and scientific communities. At the same time, such a joint mission could enhance the scientific return of the Pluto mission, provide Russia with its first entrée into outer Solar System exploration, and reduce NASA mission costs.

The basic architecture of the joint US Russian Pluto mission accomplishes these goals by launching the Pluto flyby spacecraft on Russian Proton or Molniya vehicles equipped with some combination of US and or Russian upper stages, and carrying a Russian built atmospheric probe, called the Pluto Drop Zond, to enhance the Pluto mission by entering Pluto's atmosphere and studying the planet until it impacts the surface. The Pluto Express sciencecraft would be initially put on a course to impact Pluto, and then about 30 days out from encounter, the Drop Zond would be oriented, spun up for stabilization, and released to fly on its own. Then the main sciencecraft would perform a deflection maneuver and be retargeted to miss Pluto and execute its nominal flyby encounter.

As the Drop Zond nears Pluto, the main sciencecraft would receive encounter data transmitted by the Zond and store it on board the SDS DRAM. The Zond would perform in-situ measurements of Pluto's atmosphere and possibly take images of the planet as it neared impact. After the Pluto encounter is completed, the Zond data would be played back for transmission to Earth.

With the opportunity to fly the Russian Drop Zond entry probes into Pluto's atmosphere and down to (destructive) impacts on its surface, it becomes possible to augment the 1a objectives of the Pluto mission with additional, entry probe objectives for the Drop Zond. However, owing to its limited mass, power, and data transmission capabilities, the Drop Zond can carry out only a few carefully chosen investigations.

The Pluto Joint Science Steering Group (PJSSG) evaluated a broad suite of possible investigations and scientific objectives for the Pluto Fast Flyby Drop Zonds. Among the possible investigations evaluated were:

1. Ultra-High Resolution Surface Imaging of Pluto and or Charon
2. In-Situ Atmospheric Studies, including hazes, of Pluto (and Charon, should it possess a detectable atmosphere)
3. Studies of Pluto's Surface Thermal Properties
4. Better Measurements of the Higher-Order Gravitational Moments of Pluto Charon
5. Studies of the Particle and Fields Environment Around Pluto and Charon
6. Searches for Dust around Pluto Charon

Technical and or cost limitations on the Drop Zond and its payload argued against candidate objectives (1), (3), and to some extent (5). The low potential for unique scientific return from the various candidate objectives argued against (1), (6), and (4). The PJSSG concluded that the most important contributions the Russian Drop Zond could make to the Pluto Fast Flyby mission were in area (2), in situ atmospheric studies. Taking into account the power, mass, data storage and transmission, and entry stability characteristics of the envisioned Drop Zond, the PJSSG identified the following strawman entry payload that accomplishes the Drop Zond 1a objective:

- Priority I: *Mass Spectrometer or Mass-Energy Retarding Potential Analyzer Objectives*: Detect minor species in Pluto's atmosphere, including possible noble gases, and the photochemical byproducts of Pluto's atmosphere; measure the mixing ratios of both minor and major species in Pluto's lower atmosphere; determine the kinetic temperature of the atmosphere as a function of altitude.
- Priority II: Wide-*Angle Limb Imager Objectives*: Study the density, vertical structure, distribution, and optical properties of Pluto's limb hazes; measure limb topography.
- Priority III: *Accelerometer Objectives*: Measure Pluto's atmospheric density structure.
- Priority IV: *Particle Sensor Objectives*: Measure Pluto's atmosphere and solar wind interaction and constrain or detect the presence of a magnetic field on Pluto.

The scientific objectives of these investigations largely require in situ sampling, and complement the science to be accomplished by the Pluto flyby spacecraft. In addition, the Limb Imager will produce exciting images of Pluto as the Drop Zond makes its terminal descent.

A joint US-Russian mission to reconnoiter the last of the nine known planets offers strong programmatic benefits to both sides. For the US, collaboration can lower costs to NASA, largely in the area of the launch vehicle. For Russia, collaboration can provide experience in long-lived mission technologies necessary to open the door to the outer Solar System, which Russian space vehicles have not yet visited.

9.2. JUPITER/IO FLYBY

A Jupiter flyby which is required for some launch vehicle options would allow investigation of Io both by the payload of the main spacecraft and by a probe carried by one of the two spacecraft. The experiments and or Io probe itself could be provided as one element of a collaboration with DARA. We first discuss the science to be gained from such a flyby, and then outline possible investigations enabled by international cooperation.

9.2.1. Science at Io

Research in the last three decades has shown that Io is one of the most remarkable bodies in the Solar System. It has appropriately been called “a wonderland in physics and chemistry”. Among the reasons for the exotic physics of Io the occurrence of strong tidal heating with a total power of several 1013 Watts is the most important one. It makes Io the volcanically most active body in the Solar System. The discovery of many active volcanic plumes was one of the most dramatic results of the Voyager 1 flyby at Jupiter in March 1979. The surface of Io is controlled by volcanic processes in contrast to most other surfaces in the outer Solar System which are shaped by impact processes. The topography and distribution of heat flux over the surface of Io constitute important sources of information on the outer parts of its interior. Models of Io's interior involve a possible iron and iron sulfide core, a mantle with the outer part molten and a lithosphere. The molten upper mantle constitutes the source of volcanism with the rising magma being the major transport mechanism to dispose of the internal heating rate. The current understanding is that Io has no dynamo generated internal magnetic field, although the present state of dynamo theory is sufficiently vague to make this a soft conclusion only.

The volcanic eruption plumes also provide the source of atmospheric gases among which SO2 has been identified by the Voyager IRIS experiment (Pearl et al., 1979) and various earth-based observations (e.g. Lellouch et al., 1992). Most of the SO2 released by the eruptions falls back to the surface or lower atmosphere where it contributes to the gas density or freezes out on the surface. An important mechanism is the freezing out or sublimation of atmospheric SO2 as a function of surface temperature. The atmosphere of Io is subject to a net loss of mass of about 10^{28} SO_2 *molecules* s^{-1} due to its interaction with the Io plasma torus which is formed by the ultimate ionization of atmospheric neutrals and is located roughly around Io's orbit and Jupiter's centrifugal equator. It has been found that most of the loss rate from Io's immediate vicinity is in the form of neutral molecules and atoms and only little is lost as ions, i.e. ultimate ionization occurs at some distance from the satellite.

Whereas the surface temperatures are determined by the balance between absorption of sunlight, thermal infrared radiation and heat conduction into the surface, the atmospheric temperatures are determined by solar EUV absorption, infrared radiative cooling and heating as well as plasma heating and Joule heating leading to temperatures above 1000 K at some 100 km (Strobel et al., 1994). Surface temperatures range from 90 K to 130 K on the surface not directly affected by volcanic processes and to several 100 K at volcanic eruption sites. The surface pressure of SO2 in essentially global models derived from HST observations (Balleston et al., 1994) ranges between 0.1 and 1 x 10,9 bars and may be even lower in very cold regions. 10,7 bars has been derived from Voyager 1 observations near a volcanic plume. The substantial pressure differences may lead to supersonic winds near the surface (Ingersoll et al., 1985; Moreno et al., 1991). Ion drag in the upper atmosphere leads to even hypersonic winds, although very little has been done to investigate this. In addition to SO_2 other neutral species like *SO*, *S*. *O* etc. are expected as atmospheric constituents. They form extended neutral clouds at some distance from Io. An important minor species is Na also forming a neutral cloud of banana shape in the downstream direction. Its atmospheric chemistry is unclear. An interesting subpopulation of Na atoms is not lost via ion drag but by charge exchange reactions around and above the exopause.

The observational situation for Io's ionosphere has been more favorable, because two ionospheric profiles were derived from the radio occultation measurements obtained during the Pioneer 10 encounter with Jupiter. The electron density profiles with a maximum density of about $7x10^4cm^{-3}$ can be explained at least in principle by electron collisional ionization. Modelling calculations show that plasma transport driven by the interaction with the torus must play an important role in Io's ionosphere. Ion species expected are SO_2^+; SO^+; O^+; S^+ etc. as well as Na^+ and Na-bearing molecular ions. On the downstream side an ion tail must be present with a loss rate of well below one ton per second, however.

The electrodynamic interaction between Io's atmosphere ionosphere system and the plasma torus is initially driven by the motional electric field of about 110 V km as seen by an observer on Io. Due to the ionospheric conductivities a current is driven through Io's atmosphere away from Jupiter. The condition of non-divergence of the current produces polarization charges which tend to shield the initial electric field leading to much lower electric fields inside Io's lower atmosphere ionosphere. A reduction to about one tenth of the unperturbed electric field is suggested by modelling results (Wolf-Gladrow et al., 1987) and the velocity distribution of sodium atoms produced by charge exchange. The drift speed is then in the vicinity of 5.7 km/s. This strong reduction of drift speeds near Io is contrasted with accelerations on the flanks up to about 100 km/s.

The current through Io's ionosphere is continued by a system of mostly field-aligned currents in Alfven wings radiated northward and southward from Io. These Alfven wings lead to a complex system of waves reflected at the torus boundary and at Jupiter's northern and southern ionosphere. The Alfven wing picture has been confirmed by the Voyager particle and field instrumentation during the Voyager 1 encounter in March 1979. The Alfven wing regions north and south of Io are expected to have many similarities with the auroral oval and polar cap regions which are some of the physically most interesting regions of the terrestrial magnetosphere. Particle acceleration and auroral phenomena are expected to play important roles. Apart from the global picture Io's upper atmosphere and plasma environment are relatively little understood yet. The same is true for the source region of the Alfven wings which is also the transition region between the lower atmosphere of Io and the neutral clouds as well as the lower ionosphere and the plasma torus. Many interesting dynamical processes are expected to occur in this region.

The electrodynamic interaction between Io and the Jovian magnetosphere is unique in the Solar System. The large power involved of about 10^{12} Watts in the Alfven wing system is due to a combination of favorable factors. It is expressed by the fact that Io is by far the largest mass source for the magnetosphere of Jupiter, the largest magnetosphere of the Solar System, the influence of which is even felt inside the Earth's orbit (in the form of relativistic electrons).

The current picture of Io is expected to be greatly enhanced in the next decade by Galileo (and also possibly Cassini) with many remote sensing observations and a Galileo orbiter flyby at an altitude of closest approach of 1000 km. Also Earth-based observations will contribute mostly to the global picture. Because of the nature of these observations many important questions will remain unanswered, however.

9.2.2. *Mission options for Exploring Io with Pluto Express*

An encounter trajectory passing inside $6R_J$ during the flyby at Jupiter would make observations of the complex system of plasma disturbances generated by Jupiter's satelite Io possible if a particles-and-fields set of experiments is included on the two main spacecraft. After the Voyager 1 and Galileo encounters at Io the most interesting target will be a passage through one of the Alfven wings not necessarily at a close distance from Io. An additional objective related to Io would be a radio occultation of Io's ionosphere. Last but not least an Infrared Thermal Mapper dedicated to the global mapping of infrared thermal emissions from Io's surface could be an important tool to diagnose the energy budget of Io's lithosphere.

A much more far reaching possibility is the deployment of an Io probe from the Pluto Express spacecraft during the Jupiter flyby phase. From the consideration of the current status of Io science it can be deduced that the scientifically most urgent objective for such a probe would be to study the neutral atmosphere ionosphere system and the transition from the neutral atmosphere and ionosphere to the neutral clouds and plasma torus, respectively, which involves part of the plasma dynamics describing the Io torus interaction. The following instruments are candidates for a payload of an Io-Probe:

neutral ion mass spectrometer
magnetometer
radio science investigation

The neutral ion mass spectrometer with limited mass resolution will have the highest priority. The swing-by at Jupiter towards Pluto will always involve prograde fly-by trajectories with impacts on or grazing fly-bys at Io near Jovian local evening. Relative velocities will be of the order of 10-15 km/s. The probe will approach the upstream face of Io in the sense of torus ow or the trailing face in the sense of Io orbital motion.

9.3. PARTICLES AND FIELDS PAYLOAD

The interaction of Pluto's atmosphere with the solar wind represents an important additional goal partly contributing to Category 1a science objectives. A payload to address these issues could be implemented as part of a collaboration with DARA. A strawman payload might include a pickup ion sensor combined with the capability to measure solar wind protons and other energetic particles, a magnetometer and a wave detector. A large field of view and some mass resolving capability to cover proton, alpha particles and pick-up ions derived from the neutral atmosphere is required. Some target measurement values for such a package include the density (0.005 - 1 cm^{-3}) and velocity distribution of solar wind protons (50 - 600 $km\ s^{-1}$); the fluxes of pick-up ions (with speeds < 1200 $km\ s^{-1}$); waves (up to 50 kHz); the mass spectrum of pick-up ions (1-4, 12-15, 16- 19, 26-33 and 40-45 amu/charge); magnetic fields (0.1 to several hundred *nT*); fluxes of energetic particles (up to ~ *MeV/nucleon*); and the electron spectrum (from 10^2 - 10^6 *eV)* (M. Neugebauer et al., *Pluto Fast Flyby Space Physics Science Definition Team*, unpublished report, 1993).

Taking into account the different plasma conditions at Jupiter the particles and fields payload could also yield important new results at Jupiter as explained in the section on the Jupiter flyby option.

Since the Pioneer 10 and 11 and Voyager spacecraft carried no dust experiments for measurements in the outer heliosphere interplanetary dust Pluto Express: Report of the Science Definition Team measurements will be restricted to distances less than 10 AU after the Ulysses, Galileo, and Cassini missions which carry advanced dust experiments. A simple dust detector on the Pluto spacecraft could explore the dust population outside 10AU, although it would require a limited cruise operations mode. Such an experiment could be implemented through international cooperation.

10. Mission Operations Concept

In order to reduce significantly the cost of mission operations during the long flight to Pluto, a concept has been developed by JPL personnel John Carraway, R. Bruce Crow, Jay Wyatt and Richard Doyle, called Beacon Cruise. It is planned that the HGA will continuously be pointed at the Earth during cruise with the receiver operating and the transmitter broadcasting an uncoded carrier with three possible tones: everything's okay, there are data ready to downlink, or there is a serious problem which needs immediate attention.

This carrier will be receivable by smaller ground stations than are not normally associated with deep space missions, so that much of the sciencecraft health monitoring can be performed on a loosely scheduled basis by non-JPL partners (i.e., universities, industry, other NASA centers) or other non-Deep Space Network (DSN) facilities. If the carrier indicating a problem is received, then the sciencecraft will be tracked more intensively by the DSN, and an emergency response team will be quickly assembled to resolve the problem.

The Pluto sciencecraft will feature a large degree of autonomy, self- monitoring, internal fault protection in both software and hardware, and automated on-board resource management in order to effect a very small ground team during cruise. Some months before the Pluto Charon encounters, a larger ground team will be assembled to perform the final planning and implementation of the science encounter phase of the mission.

11. Science Management Plan

11.1. DATA MANAGEMENT AND RIGHTS

It is NASA's policy that data from its space flight missions be made available to the public and the scientific community without delay. There will be no exclusive use period for Pluto Express mission data, and they will be deposited in the Planetary Data System/NSSDC archive following the shortest possible validation period.

11.2. SCIENCE TEAM SELECTION AND MANAGEMENT

The Pluto Express sciencecraft philosophy requires that individuals selected to produce the science investigation work closely with JPL and other team members on producing investigation hardware and the spacecraft systems which support the investigations. It is anticipated that the selected teams will be small, and consist mainly of those who will design hardware and software for the mission. Scientists whose role would be primarily in the areas of data reduction and analysis, and interpretation of the resulting information will not be selected as part of the initial team in order to save costs.

After launch and as the spacecraft nears its science targets, NASA will select a broader team of scientists to provide the expertise required to successfully conduct the observations, and reduce, analyze and interpret the data. The core of the team, it is anticipated, will be those who designed the investigations during the pre-launch phase, with possible changes reflecting career moves, retirements, etc. The intent is to retain the crucial expertise needed to fulfill the science investigation, while bringing in new people who can maximize the value of the science returned from the mission.

12. Summary

The Pluto Express mission represents an extraordinary opportunity for the United States and potential international partners in two respects. First, the scientific importance of this most distant planet has increased very substantially over the past ten years. The complexity of physical and chemical processes in the Pluto-Charon system has come to be understood from Earth-based studies, confirming that a flyby mission would be rich in phenomena to be investigated and insights gained into how planetary atmospheres, surfaces and interiors work. The newly discovered trans-Neptunian objects appear to be part of a reservoir of relatively primitive material from which short period comets originate, and of which Pluto (and perhaps Triton) represent high-mass endmembers. Study of Pluto's composition, and possible investigation of one or more Kuiper Belt objects would provide cosmochemical information of enormous value for examining outer Solar System and molecular cloud processes associated with Solar System formation and delivery of volatile and organic material throughout the early Solar System (including, perhaps, to the Earth).

Second, the implementation of Pluto Express as the first low-cost, high-technology sciencecraft opens the door to a program of deep space exploration in a fiscal environment which is tightly constrained. In the absence of a new approach to lowering cost and maintaining or increasing scientific capability using new technologies, this nation will be unable to pursue missions in the outer Solar System, an area of keen scientific interest and one in which the United States has to date been a clear leader. At the same time, Pluto Express represents an opportunity for international participation and collaboration in the spirit of previous and ongoing planetary missions.

Pluto captures the imagination as the most distant of the nine planets, and the one as yet unvisited by spacecraft. Public excitement in, and expectation of, a first Pluto mission has been high throughout the many years in which several types of Pluto missions have been studied. A Pluto Express mission will have little or no difficulty in maintaining a high positive profile in the public and political arenas, and hence be a valued asset to the NASA Space Science Program. NASA's aggressive pursuit of this project will ensure that the United States and its international partners do not shrink their space frontiers, but instead build a flight capability that will define and enable a planetary exploration program of the 21st century worthy of a visionary humanity.

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