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KUIPER EXPRESS: A SCIENCECRAFT

D. H. Rodgers[a], L. Alkalai[a], P. M. Beauchamp[a], G.-S. Chen[a], M. P. Crisp[a], R. H. Brown[a],
J. M. Davidson[a], D. Huxtable[d], P. A. Penzo[a], S. W. Petrick[a], L. A. Soderblom[b],
A. Stewart[e], G. Vane[a], **R.** V. Yelle[c]

[a] Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

[b] United States Geological Survey
Flagstaff, Arizona 86001

[c] Department of Astronomy, Boston University
Boston, Massachusetts 02215

[d] Olin Aerospace Corporation
Redmond, Washington

[e] The Boeing Company
Seattle, Washington

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Abstract

The Kuiper Express is a mission to achieve the first reconnaissance of one of the primitive objects in the Kuiper Belt. The objects in the Kuiper Belt are thought to be the remnants of the planetesimal swarm that formed the four giant planets of the outer Solar System. These objects, because they are far from the Sun, have not been processed by solar heating and are essentially in their primordial state. This makes them unique Solar System objects and their study will provide information on the composition of the solar nebula that cannot be extracted from a study of objects in the inner Solar System or of the giant planets within which gravitational fractionation of the constituents has taken place.

The Kuiper Express is a sciencecraft mission. It will be launched using a Delta vehicle and will use solar electric propulsion to shape its trajectory in the inner Solar System, while executing two earth gravity-assist flybys. It will also execute flybys of main belt asteroids, Mars, Uranus, and Neptune/Triton en route to its target in the Kuiper Belt, where it will arrive roughly ten years after launch. It will use no nuclear power. The surface constituents and morphology of the objects visited will be measured and their atmospheres will be characterized both in emission and absorption (against the Sun).

The sensor system and spacecraft subsystems are highly integrated into one unit, with an emphasis on shard functionality, thereby greatly reducing cost, and increasing shard redundancy. Mission operations costs are reduced because the design permits the craft to function in a largely autonomous mode. operations costs are further reduced by the design of the integrated sensor system for which data collection is optimized when the channels are operated in a time multiplexed fashion. Thus, "conflict free" sequencing is achieved prior to launch, The cost of the detailed design, fabrication, and launch of the Kuiper Express is consistent with the $150M limit set by the NASA Discovery Program.

I. The Kuiper Belt

The Kuiper Belt was postulated to exist by astronomer Gerard Kuiper, who wondered why the series of giant planets, Jupiter, Saturn, Uranus, and Neptune, stopped so abruptly at Neptune.[1,2] It is unlikely, he reasoned, that the solar nebula itself was cut off sharply beyond Neptune. What then had become of the remaining matter? Kuiper assumed the generally accepted picture of the formation of the planets, with the cold matter in the outer part of the nebula condensing first into planetesimals, comet sized bodies consisting mostly of ice. Then over a longer time these planetesimals collided, stuck together, and gradually accumulated into the planets. According to this picture, the planetesimals in the region beyond Neptune were too far apart and too slowly moving to accumulate to form another large planet. But what happened to them and where are they now? Kuiper concluded that the population of planetesimals beyond Neptune is still there.

With this argument, Kuiper identified a new reservoir of comets, much closer to the Sun than the Oort Cloud,[3] but, unlike the Oort Cloud, lying in the plane of the planets. Kuiper imagined this population of objects to extend roughly from 40 AU to 100 AU from the Sun. He estimated their total mass based on the masses of Uranus and Neptune to be roughly ten Earth masses.

Experimental evidence for the existence of a comet belt beyond Neptune was nonexistent (or unrecognized) at the time of Kuiper's original publication. The possibility of direct detection by observation of reflected sunlight was rejected by Kuiper himself, and by others,[4] because they would be too faint to detect. For example, even a 100 km diameter object at 40 AU is approximately 22nd magnitude. Moreover, most of the Kuiper objects were thought to be "comet sized," between 1 km and 10 km in diameter. Thus, direct detection was beyond the reach of the astronomical instruments available at that time.

A number of unsuccessful efforts were made to find dynamical evidence for the existence of these objects in the form of perturbations of the orbits of Uranus and Neptune. More recently studies by Anderson and Standish[5] of tracking data from Pioneer 10 and by Hamid et al.[6] of the motions of periodic comets have set bounds on the total mass of the Kuiper objects of <0.5 Earth masses out to 40 AU and <1.3 Earth masses out to 50 AU.

The first direct evidence for the existence of the Kuiper belt came from a reexamination of the orbit data (some of it centuries old) of short-period comets by Duncan et al.[7] These authors compared the observed statistics of short period comets (semi-major axes ≤ 100 AU) with computer simulations based On two theories of their origin. They showed unequivocally that the observed population of short period comets, with prograde orbits lying in the plane of the planets, could *not* be derived from the observed population of long period comets, which had randomly aligned orbits, by gravitational interactions with Jupiter and Saturn. However, the short period comets were very well described by a model in which they were perturbed into the inner Solar System from a comet belt beyond Neptune.

A second body of experimental evidence began accumulating in 1992 with the actual discovery[8] of the first directly observed object in the Kuiper Belt, denoted 1992 QB1. This was followed in the next two years by the discovery of an additional eleven trans-Neptunian objects, ranging in heliocentric distance from 32 AU to 42 AU. These objects are, as Whipple[4] had predicted, about 22nd magnitude in apparent brightness and thus on the order of 100 km in diameter. Presumably they are the larger members of a population which numbers, according to various estimates,[2,9] between 4 *x* 108 and 10^{13}. Their detection has been enabled by the advent of more large instruments (e.g., the Keck Telescope and the Hubble Space Telescope) and more sensitive charge coupled detection devices. The rate of new detections is now undoubtedly accelerated by the heightened interest in this once almost mythological realm of eternal darkness, cold, and ice, which may hold in its frozen grip the key to understanding the formation and evolution of the Solar System.

11. A Sciencecraft for Kuiper Express

The authors propose the development of a sciencecraft to perform an initial reconnaissance of the Kuiper Belt. We call this craft (and the mission on which it will be sent) the *Kuiper Express*, in honor of the astronomer Gerard Kuiper, who was the first to realize that a population of comets must exist beyond the orbit of Neptune as a remnant of the formation of the planets. We have termed it the *Express* because of the short time it will take to arrive at the inner edge of the belt, reaching the orbit of Neptune (at 30 AU) only ten years after launch. The Kuiper Express will utilize the Sciencecraft Approach which is described in detail in a companion paper to this one.[10] We repeat this description briefly here; see Ref. 10 for further details.

The design of a sciencecraft begins with the definition of the mission science objectives. For the Kuiper Express, the objectives are to fly by an object in the Kuiper Belt and determine its size, shape, mass, density, albedo, and rotation rate. We will characterize the impact bombardment history as it relates to early accretional collisional evolution. We will map surface composition, identify mineralogical, volatile, organic species, understand regolith aging processes (freshly exposed versus darkened /altered). We will map thermal characteristics of the surface (temperature, thermal inertia, bolometric bond albedo). We will search for satellite companions.

Based on these objectives, a set of measurement requirements was inferred, including long focal length multiwavelength telescope observations, with optimized infrared, visible, and ultraviolet readout. These requirements suggested that we develop a sensor system derived from the Planetary Integrated Camera Spectrometer (PICS). A sensor system concept based on PICS has been developed for the Kuiper Express Mission. We call this derivative device the Kuiper Integrated Sensor System (KISS). The KISS performs imaging spectrometry in four windows at infrared, visible, and ultraviolet wavelengths. In addition, it performs imaging in the visible wavelength range. A detailed description of the PICS sensor system is presented elsewhere.[10]

An observational sequence was developed to provide the set of required measurements. This sequence was based on the postulated flyby of a 500 km diameter Kuiper Belt object. This sequence will provide a complete coverage of the sunlit face of the target object in each of the five instrument channels at the highest resolution possible. It was found that a closest approach distance of 10000 km optimized this data set. The critical data set is recorded in the final hour before closest approach, and the data volume for this data set is about one gigabit. This observational sequence was constrained only by the low level of illumination at approximately 40 AU from the Sun and by the fact that the

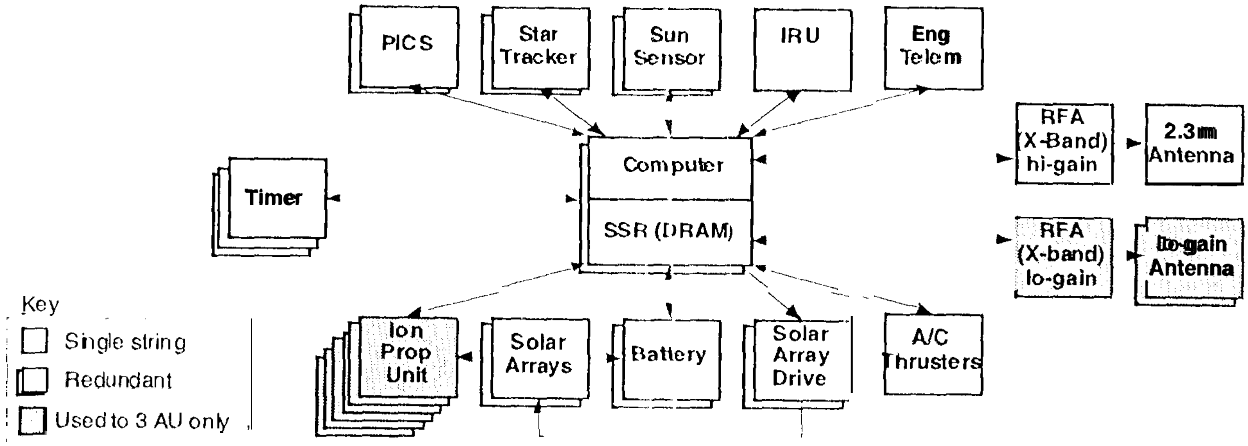

Figure 1. Kuiper Express Sciencecraft functional block diagram.

sciencecraft would be traveling approximately 20 km/sec (about 4.5 AU/yr). This latter constraint was adopted *a priori* because any trajectory which led to a lower flyby speed would also result in an unacceptably long mission.

With the sensor system and the observation sequence defined, the design of the sciencecraft hardware subsystems and subsystem architecture could be begun. This development process and the resulting subsystems are described in detail in Ref. 1(1 and will not be repeated in full here. We summarize that process by presenting a functional block diagram containing the logical architecture of Kuiper Express (Figure 1). The reader will note the following key features which this figure illustrates. First, the sciencecraft architecture is very *simple* which implies prototyping, integration and testing, which are both low-cost and fast. Second, the sciencecraft architecture is highly *integrated* and "subsystemles " favoring development by a highly integrated team, reminiscent of the skunkworks approach wherein one team "clews it all." Third, the sciencecraft uses advanced technology, which implies that it is highly *capable*. ‘“’

III. Kuiper Express Mission Design

The Kuiper Express Sciencecraft can be launched by a Delta vehicle in March of 1999. Figure 2 shows the craft as it will look in the Delta shroud with its solar panels folded and in space with its panels fully extended. After launch, the craft's trajectory will take it beyond the orbit of Mars, then back inside the Earth's orbit, and finally in May of 2001 back to the Earth for a gravity assist. During the first thirty one months of the mission, the Scalar Electric thrusters will operate about half the time, as shown in Figure 3, to shape the trajectory and add energy and momentum. These thrusters will shut down when the sciencecraft reaches a distance of 3 AU from the Sun in October of 2001. The trajectory to be followed by the Kuiper sciencecraft during these first 30 months after launch is shown in Figure 3. Following SEP shutdown, the Kuiper Express begins its eight-year cruise to the Kuiper Belt via Uranus and Neptune/Triton. Neptune is used for final targeting downselection for the chosen Kuiper object. Uranus permits the adjustment of the Neptune approach phase angle to optimize the trajectory for the Triton flyby. The use of Uranus and Neptune/Triton for

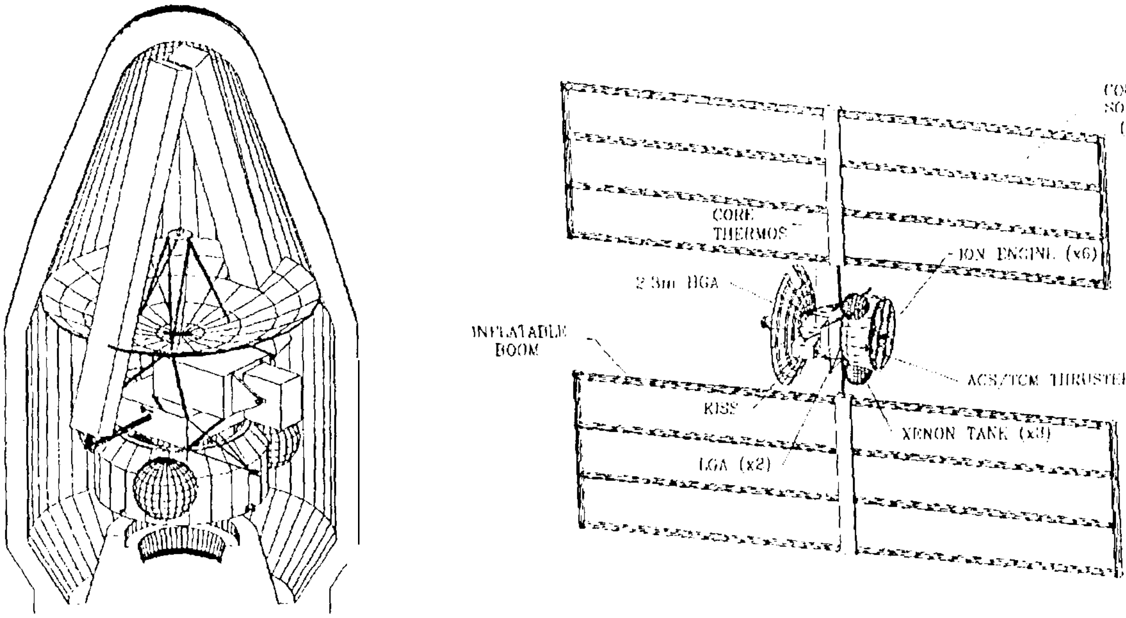

Figure 2. Kuiper Express Sciencecraft shown in the Delta shroud with its solar panels folded and in space with its panels fully extended.

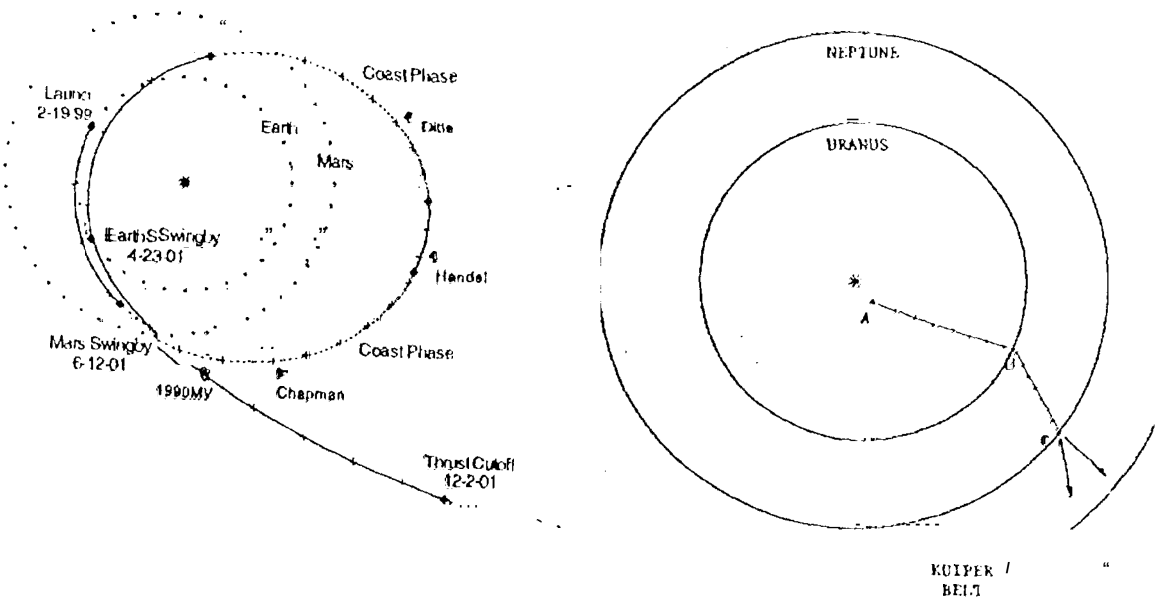

Figure 3. Kuiper Express trajectories for the inner and outer Solar System. Possible asteroid flyby candidates are shown, The tic marks in the outer Solar System denote 180 clay intervals,

trajectory shaping and target downselection will enable the Kuiper Express to add Galileo/Cassini class observations of these planets to its scientific harvest. It will thus complete a second (after Voyager) reconnaissance of the outer Solar System at a time when conditions have changed significantly. The trajectory the Sciencecraft will follow in the outer Solar System is illustrated in Figure 3.

Attitude control for the Kuiper Express is done using three different modes of control. Three-axis attitude control is used for the first two-and-a-half years of the mission. The control technique used is thrust vector control of the SEP thrusters. From SEP cutoff until shortly before the Uranus encounter, the Sciencecraft is space-stored in a spin mode about its principal axis. The spin rate needed for stability will be small, ~0.03 RPM, because of the large moment of inertia provided by the solar panels. In this mode, the solar panels will remain facing the Sun. By the time the Sciencecraft approaches Uranus (at 19 AU) the Earth/Sun angular separation has dropped below 4 c and separate pointing of the solar panels and the high gain antenna for communication and power generation is no longer necessary. Although the main driver for spin "storage" during cruise is the reduction of mission operations costs, the use of the spin mode for sciencecraft storage also serves to reduce the mass required for attitude control propellant, Before each flyby- of Uranus, Neptune, and a Kuiper target— the Sciencecraft will be despun and the attitude control system placed in a three-axis mode using gas thrusters. Following the flybys the craft will return to the spin mode.

Targeting and velocity adjustment prior to and following planetary encounters will use techniques developed and used for the Voyager Mission, but with the following critics] difference. For Kuiper Express some or all of the navigation, sequence generation and checking, and sequence execution for gravity assist flybys and science data recording will be performed on-board the sciencecraft. 'This departure from tradition is made necessary by tile very high speed of the Kuiper Express combined with the considerable latency for communication with the miter Scalar System, There simply won't be time to phone home for instructions. Targeting for the Kuiper object itself is exacerbated by its small size. Guise navigation (i.e., between encounters) will use> ground-based optical measurements, probably augmented by data from the Hubble Space Telescope, using the Hipparcos optic-a] star catalogue for coordinate frame definition. Final targeting for the Kuiper flyby will use the onboard sensor system (KISS) to provide optical navigation data. The closest-approach distance (assuming a 500 km diameter target object) that will optimize data recording for the KISS installment is about 1000 km. We estimate that we can attain this distance within ±200 km.

IV. Kuiper **Science Data Collection**

The **observational** sequence of events during the Kuiper object encounter is constrained by the geometric factors noted above (diameter of the Kuiper target object, Sciencecraft velocity, and distance of closest approach). We have further constrained the design of the measurement sequence by requiring that a nearly complete coverage of the illuminated face of the Kuiper object be made in each one of the five instrument channels- -near and far infrared (SWIR, LWIR), visible (VI S), and ultra-violet (UV) spectrometers and visible imaging- with the highest resolution possible. The optical design has been chosen such that the there is a distinct regime or range of distances from the target (and hence times before closest approach) for each of these channels which is ideally suited for data recording. This can be seen from Figure 4 which depicts the mapable fraction of the Kuiper target as a function of time before closest approach for each of the instrument channels, In this figure, we also see depicted the times when each channel will be accumulating data. As these two figures indicate, essentially the entire gigabit of critical encounter data will be collected in the final 48 minutes before closest approach.

With the collection of the data as described above, all the mission scientific measurement objectives will be met except one: the determination of the target object's density. Thus, we will execute a passive gravity experiment. A simple radar reflector (a sphere

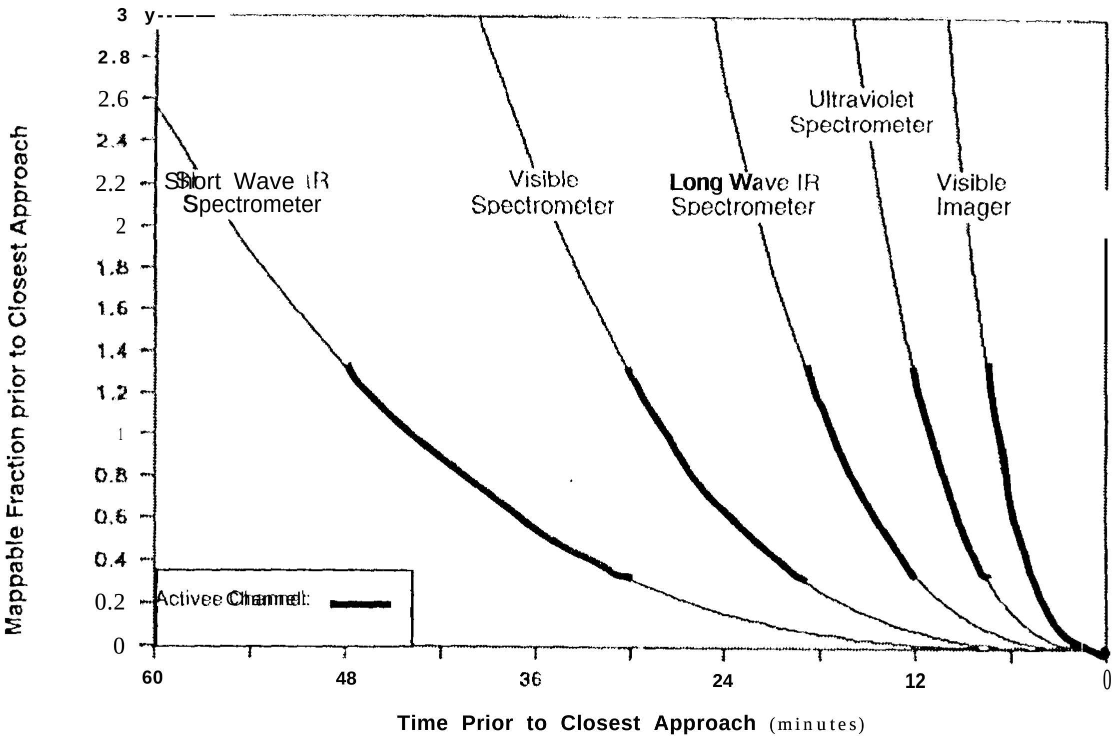

Figure 4. Mapable fraction of Kuiper target object vs. time from closest encounter. Design of the spectrometer permits "conflict free" time multiplexing of the five channels.

or three-plane corner reflector) will be released a few hours before closest approach and will pass close to the surface of the target. Ranging to this probe by the Kuiper Express will determine its gravitational deflection and thus the mass of the target. The final details of this experiment have not been completely defined, as they depend critically cm flyby geometry, velocity, and mass of the Kuiper object. The release of another probe to impact cm the surface of the Kuiper object itself, providing flash spectrometry data, is also being considered as an option,

V. Probing the Kuiper Belt by Means of Occultation Astronomy

Two authors[1,11] have discussed the intriguing possibility that the objects in the Kuiper Belt might be studied from the Earth by means of occultation astronomy. The proposed experimental apparatus is quite simple in concept and its construction and operation would be relatively inexpensive to carry out, being within the means of amateur astronomers and high school students. We repeat the essence of their proposal here, since we plan to incorporate screw version of this into our educational outreach program.

The principal behind the occultation experiment is this. As an Earth-based observer views the heavens and as the Kuiper objects move in their orbits, from time to time one will pass in front of a distant background star. When such an event happens, the occulted star will momentarily blink out and then reappear. The frequency of these events give's information cm the number of Kuiper objects. Their duration gives information on the objects' sizes. In addition, if the measurement is made in two colors, the dependence of the diffraction fringes on wavelength discloses the distance to the occulting object.

The frequency of occultations depends cm the number of objects in the Kuiper belt. Predictions of this number have ranged from 10^{13} (Kuiper[2]) to 4×10^{8} (Weissman[9]). If the greater of these two values is correct, then a small telescope with automatic detecting equipment to watch 100 stars continuously might see occultations at an average rate of two per hour. The duration of these occultations depends, of course, cm the sizes of the occulting objects, which most authors place in the range of 1 km to 10 km. in the case of a 1 km object, the occultation will have a maximum duration of about 30 msec, easily measurable using modern electronic equipment. The edge of the "shadow" cast by the Kuiper object on the Earth by the light from a distant star will be made fuzzy by diffraction. The extent of this fuzzy region depends on the distance of the object from the Earth. For a 1 km diameter object at a distance of 50 AU, the extent of the fringe pattern will be comparable in size to the shadow itself.

Techniques for dealing with the effects of atmospheric turbulence (twinkling) and for identifying and rejecting uninteresting occultation events (e. g., from nearby asteroids, from Earth orbiting debris, and from airplanes, birds and bats) are described by Bailey[11] and Dyson[1] in their excellent papers.

The equipment required to start out on a small scale is minimal, consisting of two 0.5 meter diameter telescopes, photometers, data links with accurate timing, and a computer to collect and correlate a considerable volume of data in real time. If occultations are observed, the system could be expanded. If no occultations are observed, the measurements provide invaluable new information, as they set an upper limit on the number of objects in the Kuiper Belt, No direct experimental data fixing this number currently exists.

VI. Uranus, Neptune, and Triton: A Science Bonus

The planned flybys of Uranus and Neptune are not ***required*** for the Kuiper Express to reach an object in the Kuiper belt. A Neptune flyby was included originally to give us a late (almost ten years after launch) opportunity to downselect to the scientifically most attractive target object. Neptune, being large, gives us a maximum trajectory bending angle of about 45°, either in or out of the ecliptic plane. This strategy makes good scientific sense since new Kuiper objects arc' being discovered at the rate of about five a year, and this rate is increasing. Once the Sciencecraft is launched, the region of the Kuiper belt lying beyond Neptune will receive heightened scrutiny from the Astronomical community, leading to the discovery of more potential target objects.

Neptune/Triton

Although Neptune is being used primarily for a targeting adjustment, we will reap the scientific bonus it offers. The science objectives for the Neptune/Triton encounter have been shaped by the measurements made in 1989 by Voyager. We will study changes in Neptune's global circulation and atmospheric dynamics twenty years after Voyager. We will determine following attributes of Neptune's and Triton's atmospheres.

Composition. The composition of the atmospheres including the abundance of CH_4 in the deep atmosphere and of C_2H_2, C_6H_6, CO, and HCN in the stratosphere and search for evidence of N_2, H_2S, and other species.

Structure. The thermal structure of the atmospheres from the tropopause to the exobase.

Energy. The solar and magnetospheric energy input rates to the atmosphere.

Albedo. The bolometric bond albedo to deduce the energy balance for the Neptunian atmosphere.

Triton is one of the more scientifically interesting objects in the Solar System and has acquired its own coterie of followers in the wake of Voyager II's discovery there of "geysers" of liquid Nitrogen and other unique features. At the encounter with Triton, we will undertake the following measurements.

Post-Voyager Changes. We will search for temporal changes twenty years after Voyager (and at the peak of a maximum southern summer) in the chemical and physical nature of the surface and ongoing processes (e.g., phases of polar ices, plumes, and atmospheric transport).

Surface Composition. We will map surface composition, identifying chemical species, abundance, phase states, isotopic species (e.g., CH_4, N_2, CO, C_xH_y, H_2O) and determining the partial pressures of N_2, CH_4, CO and their relationships to the physical states of surface ice deposits.

Atmospheric Composition. We will determine the composition of thermal structure of the atmosphere, including the distribution of minor constituents, such as C_2H_2, C_6H_6, HCN, and others.

Atmospheric Dynamics. We will study the atmospheric dynamics from cloud systems and surface eolian markings and determine characteristics of atmospheric aerosols.

Energy. We will determine the solar and magnetospheric energy input rates to the atmosphere.

Uranus

A flyby of Uranus was not originally planned for the Kuiper Express mission. However, two of us (L. Soderblom/R. Brown) realized that the nodes of Triton's orbit were oriented in such a way that a spacecraft approaching Neptune from the direction of the Sun would pass no closer than 350,000 km from Triton, severely limiting the value of the science acquired in the flyby. But if Neptune were approached instead from the direction of Uranus, the significantly altered phase angle would permit an almost arbitrarily close flyby Of Triton. Thus, Uranus and its satellites were added to Kuiper's itinerary.

The science objectives for Uranus itself are much the same as those for Neptune, with the added interest from the fact that by the time the Kuiper Sciencecraft arrives, a quarter of a Uranian year will have passed since Voyager II's visit, enough for a significant seasonal change. The science objectives for the satellites of Uranus are more varied. We will make the following measurements.

Northern Hemispheres. We will explore the geologic provinces and geomorphological processes of the Uranian satellites in their uncharted northern hemispheres.

Chemical Diversity. We will explore the chemical diversity of the satellite system (e.g., enormous differences between Umbriel, Ariel and Miranda) with a remote sensing package with equivalent sensing capability to these being carried by Galileo and Cassini to Jupiter and Saturn.

Surface Composition. We will map surface composition, identifying chemical species, abundances, and mixtures of icy materials exposed at the satellite surfaces.

Correlations with Composition. We will study the correlation of geomorphology and rheology with composition of the icy materials.

Thermal Properties. We will map the temperature distributions and study the thermal properties over the surfaces.

As a final point of interest, we note that Uranus and Neptune each have moderately large satellites, (Miranda and Nereid, respectively) whose discoverer is the astronomer we honor with the name of our mission (Kuiper[12]).

V. Acknowledgment

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