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# Preliminary Scientific Rationale for a Voyage to a Thousand Astronomical Units

May 15, 1987

## NASA

National Aeronautics and
Space Administration

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California

JPL Publication 87-17

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Compiled by
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## ABSTRACT

A proposed mission to one thousand astronomical units (TAU) is currently being studied by the Jet Propulsion Laboratory. Launch date for a TAU mission is likely to be well into the first decade of the 21st century. Study of TAU has focused upon the technologies required to carry out this ambitious mission and the identification of preliminary scientific rationale for such a deep space flight.

A 1-MW nuclear-powered electric propulsion (NEP) system forms the baseline method of achieving the high velocities required. A solar system escape velocity of 106 km/s is needed to propel the TAU vehicle to 1000 AU in 50 years. The NEP system must accelerate the vehicle for about 10 years before this velocity is attained because of the extremely low thrust nature of the xenon-fueled ion engines. At the end of the thrusting phase the NEP system is jettisoned to allow the TAU spacecraft and science experiments to coast out to 1000 AU.

Another important technology for TAU is advanced optical communication systems, which are envisioned for transmitting science data to Earth. A 1-m optical telescope combined with a 10-W laser transponder can transmit 20 kbps to a 10-m Earth-orbit-based telescope from 1000 AU.

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# 1.0 PURPOSE AND SCOPE

This document describes a proposed mission to a distance of one thousand astronomical units, hence the acronym TAU. This mission is currently being studied by the Jet Propulsion Laboratory (JPL) using discretionary funding. Launch date for a TAU mission is likely to be well into the first decade of the 21st century. Study of TAU has focused upon the technologies required to carry out this ambitious mission and the identification of preliminary scientific rationale for such a deep space flight.

A 1-MW, nuclear-powered electric propulsion (NEP) system forms the baseline method of achieving the high velocities required. A solar system escape velocity of 106 km/s is needed to propel the TAU vehicle to 1000 AU in 50 years. The NEP system must accelerate the vehicle for about 10 years before this velocity is attained because of the extremely low thrust nature of the xenon-fueled ion engines. At the end of the thrusting phase the NEP system is jettisoned to allow the TAU spacecraft and science experiments to coast out to 1000 AU.

Another important technology for TAU is advanced optical communication systems, which are envisioned for transmitting science data to Earth. A 1-m optical telescope combined with a 10-W laser transponder can transmit 20 kbps from 1000 AU to a 10-m, Earth-orbit-based telescope.

TAU will provide astrometrists with a 1000-AU baseline, a unique opportunity for making parallax measurements of stars in a volume of space $10^8$ times what is available from Earth orbit, covering the range of the Galaxy and the Magellanic Clouds. Depending on the exact location of the heliopause and the progress of the Voyager spacecraft, TAU may permit the first in situ measurements of the plasma environment across the heliosphere and into the tenuous interstellar medium, sampling the galactic magnetic field, energetic particles, gas, dust, and plasma environment. The parallactic measurements will lead to improved models of astrophysical phenomenon and will combine with Earth-based and Earth-orbiting astronomical measurements to provide more accurate measurements of the distances to objects of interest for proper data reduction.

This document lists and describes the scientific rationale for TAU developed by various members of the science community. An internal JPL/Caltech TAU Thinkshop was held September 29, 1986 at the Jet Propulsion Laboratory as a kickoff meeting for developing the scientific rationale for this type of mission. Scientists who participated in the Thinkshop are listed below. Following the Thinkshop, a series of semi-weekly science presentations were made to the TAU Study Team covering all areas of science that would greatly benefit from this mission.

The proposed experiments were evaluated for scientific worth, feasibility, and uniqueness to a TAU mission. Much more science could be accomplished than listed here. However, only research that was unique to the various characteristics provided by this type of mission were included.

Changes and additions to this report are expected, as we continue to explore the science potential of TAU with the science community.

Attendees at the TAU Thinkshop, held September 29, 1986 at JPL are listed below.

| | |
|---|---|
| Joseph Ajello * | Brian Metscher |
| John Appleby | Robert Nelson |
| Bonnie Buratti | Kerry Nock |
| James Burke | Maria Ines Etchegaray |
| Dick Dickinson | Bonnie Schumaker |
| Frank Estabrook | David Sonnabend |
| Steven Federman * | Steven Synnott |
| Ronald Hellings * | Richard Terrile |
| Leonard Jaffe | Arthur Vaughan |
| Robert Korechoff | Paul Weissman * |
| William Mahoney | James Wilker |
| Warren Martin | Daniel Winterhalter * |
| Aden Meinel * | Robert Wolff |
| Marjorie Meinel | |

* Presenter

Science presentations to the TAU Study Team were given by the following.

Charles Beichman
Ronald Hellings
Dayton Jones
Jeremy Mould
Arthur Upgren

This document was reviewed by the TAU Study Team and by the scientists listed below with their respective fields of study.

Joseph Ajello - UV Science, Cosmic Abundance of Hydrogen
Martha Hanner - Dust Science
Steven Federman - Cosmic Abundance
Daniel Winterhalter - Space Plasma Physics
Jeremy Mould - Stellar Parallax
Charles Beichman - IR Science
Dayton Jones - Radio Science
Ronald Hellings - Cosmology

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## 2.0 APPROACH

The approach taken in this document for the discussion of the science rationale for a TAU mission was to divide the science into the following three areas of research: Stellar Parallax; Astronomy, Astrophysics, and Cosmology; and Space Plasma Physics.

I.   Visible and IR Stellar Parallax (Section 3.1)

   Uncertainty in Expansion Rate of Universe

   Age of Galaxy

   Galactic Structure

   Stellar Evolution

   Targets of Opportunity

II.  Astronomy, Astrophysics, and Cosmology   (Section 3.2)

   Galactic Astronomy

   Extragalactic Astronomy

   Cosmology

   Solar System Studies

III. Space Plasma Physics   (Section 3.3)

   Dust

   Energetic Particles / Cosmic Rays

   Plasma and Plasma Waves

   Magnetic Field

# 3.0 PROPOSED SCIENTIFIC INVESTIGATIONS

This section describes the investigations proposed for the unique scientific opportunity that a TAU mission provides. Discussed first is how the study is intended to be accomplished, second the value of the investigation to the scientific community, and third the advantages that TAU has over other available methods.

## 3.1 Visible and IR Stellar Parallax

A TAU mission has special significance to optical astronomy. Given our current 2-AU baseline to calculate trigonometric parallax we can accurately measure distances no further than about 100 pc. TAU can, by virtue of its 1000-AU baseline, expand the measurement of distances out to perhaps 50 kpc, which for once brings the entire Galaxy plus the Magellanic Clouds into the reach of our astronomical caliper. This expanded scale will enable a number of exciting astrophysical studies heretofore impossible. Figure 1 illustrates the astrometric capability of TAU assuming a 10% accuracy distance measurement and a 0.5-milliarcsecond star position measurement.

In addition to the wealth of astrophysical science made possible on TAU, this new distance scale will have a profound impact on science from past and future astronomical observatories. Several astronomical projects have flown or are being developed or contemplated including IRAS, Hubble Space Telescope (HST), SIRTF, AXAF, LDR, GRO and several explorers including COBE, FUSE, EUVE and QUASAT. All of these missions, several of which exploit new wavelength regimes, require accurate distances from optical astronomy in order to fully realize the potential of their measurements. TAU can provide these distances across the Galaxy and beyond.

The following is a list of just a few of the Stellar Parallax projects which might be contemplated on the TAU mission.

## 3.1.1 Uncertainty in the Expansion Rate of the Universe

The period luminosity relation

Since 1960 the estimate of the expansion rate of the Universe, the Hubble constant, has varied between 50 to 100 km/s per 100 kpc. The estimate of the Hubble constant is based upon our understanding of the astronomical distance scale, which is based upon the period luminosity (PL) relation of variable stars such as the Cepheids, RR Lyraes, and Miras. TAU will permit a direct measure of the distance to these stars. At present the use of
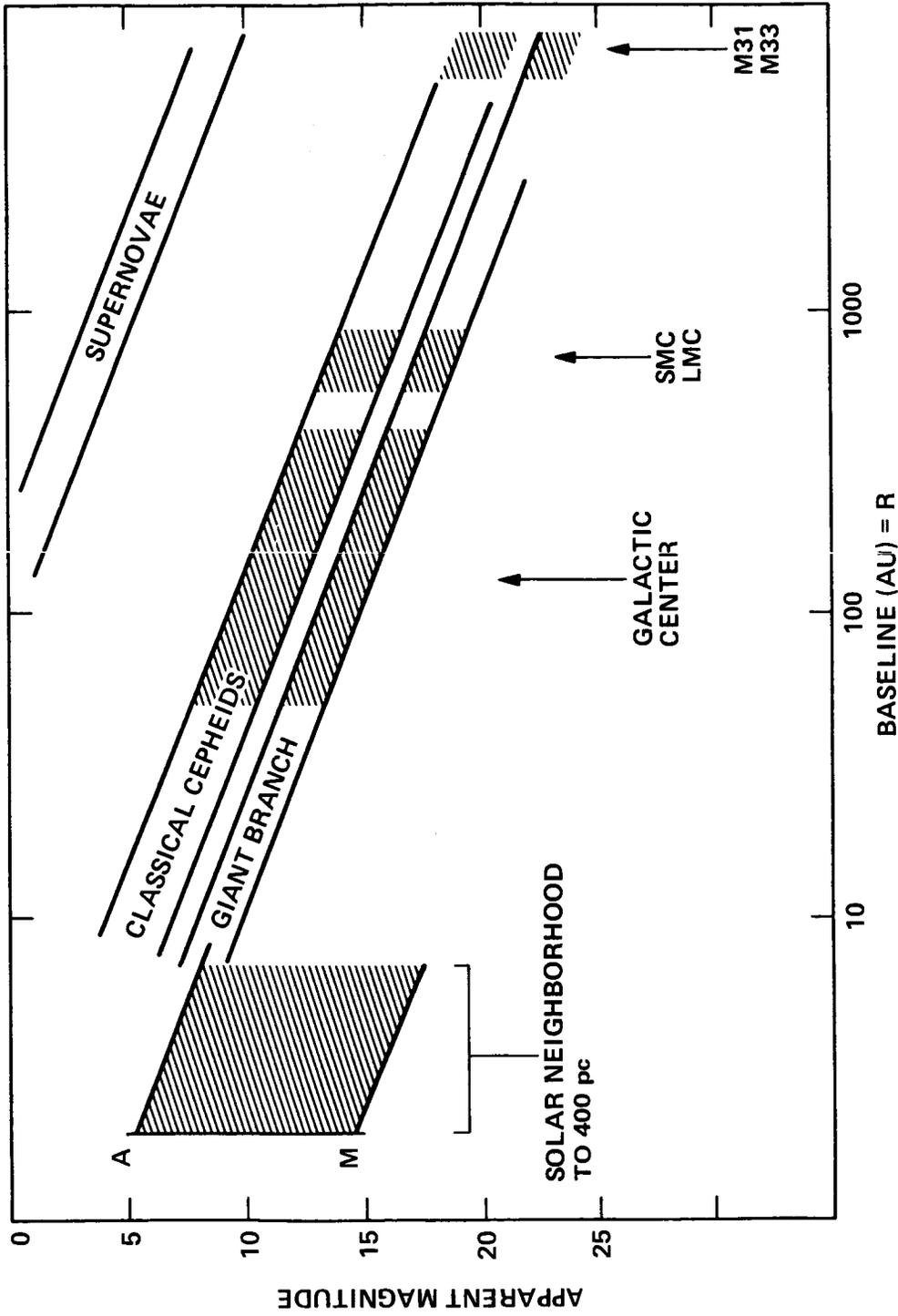
PARALLAX ERROR $\epsilon = \Delta\pi = \pm0''.0005$

ERROR IN DISTANCE MEASUREMENT $= \Delta l = \pm10\%$

$$l_{MAX} = \frac{0.1\,R}{2\sqrt{2}\,\epsilon}$$

Figure 1.    Astrometric Capability of TAU

photometric parallaxes requires assumptions of the level of local extinction to be made to calculate both the distance and the absolute luminosity of a star. A current method of calibrating the PL relation is to obtain distances to nearby star clusters by trigonometric parallax, then to fit the main sequence of more distant clusters that contain Cepheids to infer distances to them. This is called Zero Age Main Sequence (ZAMS) fitting. In this way the PL relation for Cepheids can be calibrated. The Cepheids can then be used to calibrate the Tully-Fisher (TF) relation, which relates the speed of rotation (from the width of the 21-cm emission line of neutral atomic hydrogen) with the absolute magnitude of a galaxy. The TF relation enables the measurements of distance to very distant galaxies and eventually the determination of the Hubble constant. TAU can remove the necessity for the ZAMS fit.

TAU can determine accurate parallax distances to intrinsically variable stars, within our Galaxy and the Large and Small Magellanic Clouds (LMC and SMC), e.g., Cepheids, RR Lyrae, and Miras. It will be possible to select objects with varying chemical composition to search for other parameters that may be involved in the period luminosity relation such as chemical composition, or some other higher order effect.

TAU will permit calibration of the PL curve with accurate trigonometrically determined distances, a method unavailable to Earth-based or Earth-orbiting satellites. The PL curve is the basis upon which many theories on the structure of galaxies, and astrophysical and cosmological theories are based. Trigonometrically derived distances will eliminate the ZAMS fit (or other alternative astrophysical assumptions such as the Baade-Wesselink method also used) from the distance scale ladder. A schematic comparison of the current method of determining the Hubble constant, $H_O$, with the ZAMS fit and the method available with TAU is shown in Figure 2 (Ref. 1).


3.1.2   Age of the Galaxy

Ages of the globular clusters

TAU will take the parallax of a statistically significant number of globular cluster stars. Having these "exact," trigonometrically derived distances, one can then directly fit the theoretical isochrones for the evolution of the stars to the main sequence of the globular clusters that we see. The age to be determined is the time the star takes to consume its core hydrogen. The observation is to determine the luminosity and mass of stars that have just completed their core hydrogen burning stage. Knowing the age of the oldest globular cluster will place a lower limit on the age of the universe.
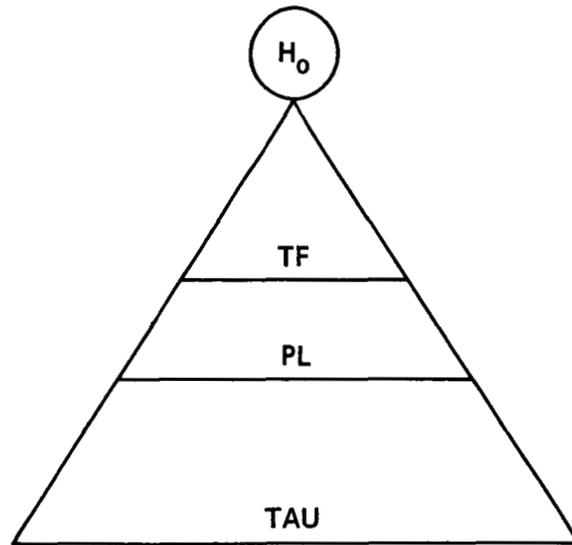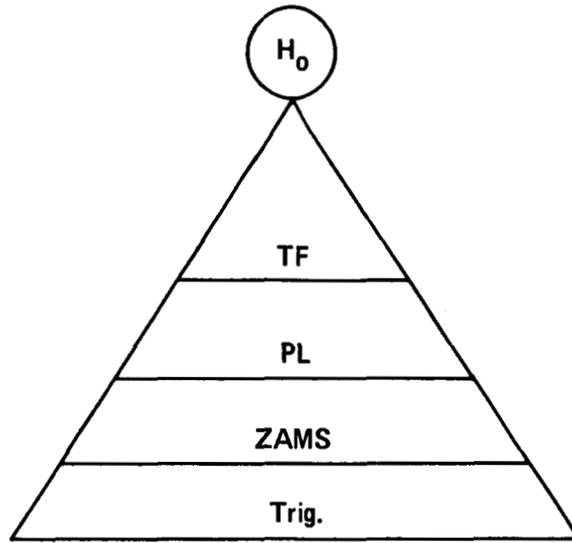
Figure 2.    Comparison of Current Method of Determining the
Hubble Constant With Method Available With TAU

### 3.1.3  Galactic Structure

The gravitational mass of the Galaxy

TAU can map the rotation curve of the Galaxy and the Magellanic Clouds. A mass model derived from this study can be used to refine theories of the formation of the Galaxy. The present method of determining the mass of the Galaxy is to do photometric parallaxes on A stars. However, this method contains large errors provided by assumptions of the interstellar extinction, which would not enter into trigonometric parallax measurements such as TAU would provide. Since TAU will measure the distances directly, it could look at late B or early A type stars that have nearly circular orbits and are at low galactic inclinations. These would be the best "test particles." The measured distances would then be combined with Earth-based measurements of the stars' velocities. With a calculation of the velocity dispersion and the distance, one can determine the galactic mass as a function of radius. The same study could be performed on the Magellanic Clouds. The Small Magellanic Cloud has recently been described as a torn-up galaxy, and would be a very interesting object of study (Ref. 1).

Dynamic temperature of the disk and halo of the Galaxy

TAU will measure the parallax distance to K giant stars, which are well distributed throughout the Galaxy. The ground-based measurements of the velocity dispersion of these stars with the TAU-measured distances will give information on the dynamical temperature of the Galaxy as a function of galactic radius. A measure of the dynamical temperature will provide a better understanding of the structure and stability of the disk and the structure of the halo of our Galaxy. Present Earth-based methods rely on photometric parallaxes of K giants; however, these stars lie on a steeply sloping branch of the HR diagram, and thus, the measure is unreliable. TAU would provide a much more accurate measure of the distances. The 50-year span of the TAU mission will also provide very accurate information on the proper motion of these K giant stars to complement Earth-based studies, and thus, one could obtain all three components of the velocity dispersion relation (Ref. 1).

Distance to the galactic center

TAU will measure the visual and IR parallax distance to M giant stars with as small an impact parameter as possible, but yet not located so close to the center of the Galaxy that the stars have the highest extinction rates. M giants are concentrated towards the center of the Galaxy. IR detectors in the focal plane of the telescope would permit the parallactic measurements to be made

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for those stars with the smallest impact parameters where the extinction in the visible is highest (up to 20 visible magnitudes).

The present day method measures distances to RR Lyrae variable stars by the use of the PL curve. RR Lyraes are not as strongly concentrated towards the center of the Galaxy as are the M giant stars (Ref. 1).

### 3.1.4 Stellar Evolution

**Early stellar evolution and resolution of cloud complexes**

Improvement on the present understanding of early stages of stellar evolution would be provided by measuring the visible and IR parallaxes of stars in molecular cloud complexes where stars are born and in stellar associations where they have been for a while. TAU will provide distances to these objects free of extinction errors. Using an infrared array in the focal plane of the detector, TAU will be able to resolve a cloud complex along the line of sight and thus model the three dimensional structure of a star-forming region. A large sample of cloud complexes may be found at about 1 kpc, with Orion even closer. TAU's accuracy will be sufficient to resolve cloud complexes in depth. Cloud complexes are a few parsecs in size and thus a 1-pc resolution at 1-kpc distance would be required. With an accuracy of 10%, this comes to a measurement accuracy of one part in 10 (Ref. 1).

**The initial mass function**

TAU will help to determine how the masses of stars are distributed as they are born, looking at stellar masses from 0.1 to 100 solar masses. Is this function broad, narrow, or bimodal? With TAU taking their parallax distances, differentiation between cluster stars and background stars that do not belong to the cluster is possible (Ref. 1).

**Binary star evolution**

Determination of the parallax distance to binary stars is another project TAU can accomplish. Presently photometric parallaxes are used to determine the distances of binary stars. This method, however, must assume that the star is a normal star, not taking into account possible mass transfer between the two stars. The study of binary stars has evolved late in stellar evolution theory. Observational constraints to study these objects is badly needed (Ref. 1).

## Late stages of stellar evolution

TAU can aid the study of how stars of different masses terminate their stages of nuclear burning. For example Wolf-Rayet stars have some kind of high mass termination point while planetary nebulae have some kind of low mass termination point. One cannot be certain of these points because, for example, the planetary nebula distance scale is uncertain by a factor of 2. Accurate distances would help greatly in studying these late stages and TAU can provide them for a much larger sample than is currently available (Ref. 1).

## Study of peculiar objects

a. Carbon Stars
   An IR detector in the focal plane of TAU's telescope will permit measurement of the parallax distances to carbon stars. These stars, though invisible to TAU in the optical range, are bright in the red wavelengths (Ref. 2).
b. Young Protostars
   At the moment only estimates are available of the distances to these objects. Parallactic distance measurements by TAU will permit a more accurate determination of their luminosity and thus of their age. The concern regarding these objects is to determine if they have completed their assemblage of mass or if they are still accreting material and building their final mass (Ref. 3).

## 3.1.5  Targets of Opportunity

As other Earth-based and Earth-orbiting astronomical observatories come to life many new objects will be discovered in our Galaxy and other galaxies. Over the life of TAU there will be requests for accurate distance determination to these objects, as well as morphological studies of objects (i.e. cloud complexes), which will be permitted by the large 1000-AU baseline. Below is a list of presently known objects for which knowledge of their distance is needed. Many more objects are expected to be added to this list through the lifetime of TAU.

Objects with unknown distance:

    O-B Associations
    Regions of high polarization (filamentary)
    Nuclei of planetary nebulae
    Nova during observation
    Nova remnants
    Supernovae

Pulsars
Open clusters, young and very old
Local Group - dwarf galaxies
Local Group - M31 bright members
                M33
                M81
S Doradus - LMC
47 Tucanae - LMC
Supernova remnants
Intergalactic objects in LMC and SMC
Infrared objects discovered by IRAS, SIRTF, LDR
New interesting objects identified by HST, AXAF, LDR, GRO


## 3.2  Astronomy, Astrophysics, and Cosmology


### 3.2.1  Interstellar Gases

It is believed that the solar system may be on the edge of a
tenuous cloud of interstellar matter (Ref. 4).  TAU would study
and characterize the properties of the interstellar cloud through
which the solar system is traversing, characterize the composi-
tion, kinetic energy, and spectra of the cloud's particles and
gases.


### Cosmic abundance of hydrogen

TAU would be able to determine the number density of hydrogen and
helium with heliocentric distance.   Since the Lyman-alpha
background from the star field is negligible, the backscatter
from the solar emission of Lyman-alpha can be used to determine
the cosmic abundance of hydrogen inside the heliosphere and in
the interstellar medium.  A 30% loss of the interstellar influx
of atomic hydrogen is predicted to occur at the heliopause.  This
model is used to explain the discrepancy between the solar system
ratio of H/He of 7/1 compared to the cosmic abundance of 12/1.
The heliopause is transparent to helium.  A measure of the radial
dependence of the number density, and especially its variation
across the heliopause transition region, is a fundamental measure
to define the interaction at this boundary (Refs. 5 and 6).


### Abundance and distribution of $He^3/He^4$, D/H, and $Li^6/Li^7$

Knowing the elemental ratios of $He^3/He^4$, D/H, and $Li^6/Li^7$, would
shed light on the development of nuclear synthesis in cosmology
and the big bang.  The $Li^6$ and $Li^7$ lines are too close together
to resolve with presently available spectrometers.  A neutral or

ion mass spectrometer may be able to provide the in situ measurements needed to determine the ratio of these elements in the solar system, across the heliopause and into the interstellar medium (Ref. 7).

Abundance and distribution of H, He, C, N, and O

TAU can determine, in situ, the cosmic abundances of these elements within the heliosphere with radial distance from the sun, across the heliopause transition zone, and in the very local interstellar medium. These particles are especially interesting in helping to define the interactions involved in these regions because of their low ionization potential. The interaction process between the solar environment and the local interstellar medium is of broader interest than just for solar system studies since similar interactions may be found in other star systems as well as other astrophysical conditions such as stellar expansion (Refs. 7 and 8). A complement of instruments to accomplish this task would include a UV photometer, a neutral particle detector (like the Ulysses MPI), and an ion particle detector (Ref. 7).


Radio Science - VLBI studies of interstellar scintillation

The angular resolution, which can be obtained with VLBI, is proportional to the baseline length in wavelengths. However, a fundamental limit to the angular resolution obtainable is the scattering size of a point source. Density fluctuations in the interstellar medium broaden the apparent size of background sources through small-angle diffraction and refraction. By measuring the effect of interstellar scintillation we can determine the turbulence properties of the interstellar medium along different lines of sight.

During the first part of the TAU cruise, at small heliocentric distances, pulsars will be used as point sources to observe the effect of interstellar medium scintillations on the propagation of the pulsar signals. This will permit determination of the scale size of the turbulence in the interstellar medium, as well as testing present models of this turbulence. Earth-based studies have indicated that the turbulence effecting radio signals has scale lengths much larger than an Earth diameter, requiring interplanetary baselines for a detailed study of the power spectrum. There is a frequency dependence to the scattering properties of the interstellar turbulence, thus sampling at a range of frequencies, i.e. 10 kHz - 22 GHz, can be used to distinguish the effects of interstellar scintillation from those of the background source. This study will aid in the development of future space-based VLBI systems (Refs. 9 and 10). In addition, we can directly measure the sizes of the radio-emitting regions in pulsars as the baseline increases.

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The VLBI system proposed would consist of a 5-meter pointable radio antenna on the TAU spacecraft and a large Earth-based antenna. This configuration would provide a VLBI system with a baseline expanding out to 1000 AU. There are two objectives to this investigation, the study of interstellar scintillation and the study of the structure of the pulsars themselves (Ref. 11).

### 3.2.2 Astronomy

Radio Science - VLBI studies of very compact radio sources

As the baseline increases the source regions within pulsars will be resolved. The signal will no longer have the coherence of a point source and thus will not be useful to probe the interstellar medium. It is at this point in the mission that the source region itself may be studied. Resolution of the radio source will help define the size of the source region and help determine, for example, the height above the surface of the neutron star where the emissions are originating. This will help constrain present models of the pulsar radio-emitting process.

At the highest possible frequencies, i.e. 22 GHz, the antenna could be used to study the structure of extragalactic radio sources, some of which are small enough to be unresolved at high frequencies on Earth-length baselines (Ref. 11).

Low frequency radio astronomy

A long wire dipole antenna would permit a study of very low frequency (10-100 kHz) radio emissions. Such emissions cannot be observed from the near-Earth environment due to the extended ionosphere and solar wind. Likely sources are galactic supernova remnants, pulsars, and burst emissions from the outer planets and heliopause. The range of frequencies to be sampled is dependent on the length of the antenna. Preferably the antenna will be no shorter than 1/2 of the longest wavelength to be sampled, although a less optimal size may be usable. Receivers for low frequencies are simple, reliable, and inexpensive (Ref. 11).

Gamma-ray burst timing and positioning

TAU can determine the location of gamma-ray sources. A TAU baseline will permit precision calculations of the time differential of the signal between TAU and Earth. This method of observation will collapse the positioning uncertainty box in one direction and will reduce the optical source hunt to a line scan problem (Ref. 12).

Gravitational lensing - quasar studies

Among the projects TAU will be able to accomplish are the following (Ref. 13).

    a. Test the hypothesis that high amplitude events are caused by gravitational lensing by individual stars in an intervening galaxy.

    b. Determine the size of the region responsible for the optical continuum emission of quasars by observing spacial luminosity differences during high amplification events (HAE).

    c. Observe brightness variations in quasars due to the transverse motion of the lensing star (and the intervening galaxy) with respect to the background quasar.

    d. Determine the number of bodies causing the gravitational lensing of observable quasars. A large sampling of quasars is required to do this study.

## 3.2.3 Cosmology

Gravitational wave detection

Using TAU and Earth as end masses of an electromagnetically tracked free-mass gravitational wave detector (Ref. 14), a stochastic background of primordial gravitational waves created by very early cosmological processes or by the big bang itself, could be detected with a sensitivity up to six orders of magnitude better than that available by other means. The wavelengths to be probed lie between 100 and $10^6$ sec. (See Figure 3.) The preferred tracking system for such an experiment is a laser transponder on board the spacecraft, but a high frequency radio system would still give an important experiment. The detection of a gravitational wave background would probe the very earliest era of the evolution of the universe and would represent a cosmological observation as important as or more important than the discovery of the microwave background or of the cosmic redshift (Refs. 14, 15, 16, and 17).

Spatial variations of G

Tracking of the TAU spacecraft provides a means to test the theory that there may be possible variations to the Newtonian inverse-square law of gravitation. The experiment would test the possibility that the Newtonian laws of motion would break down in
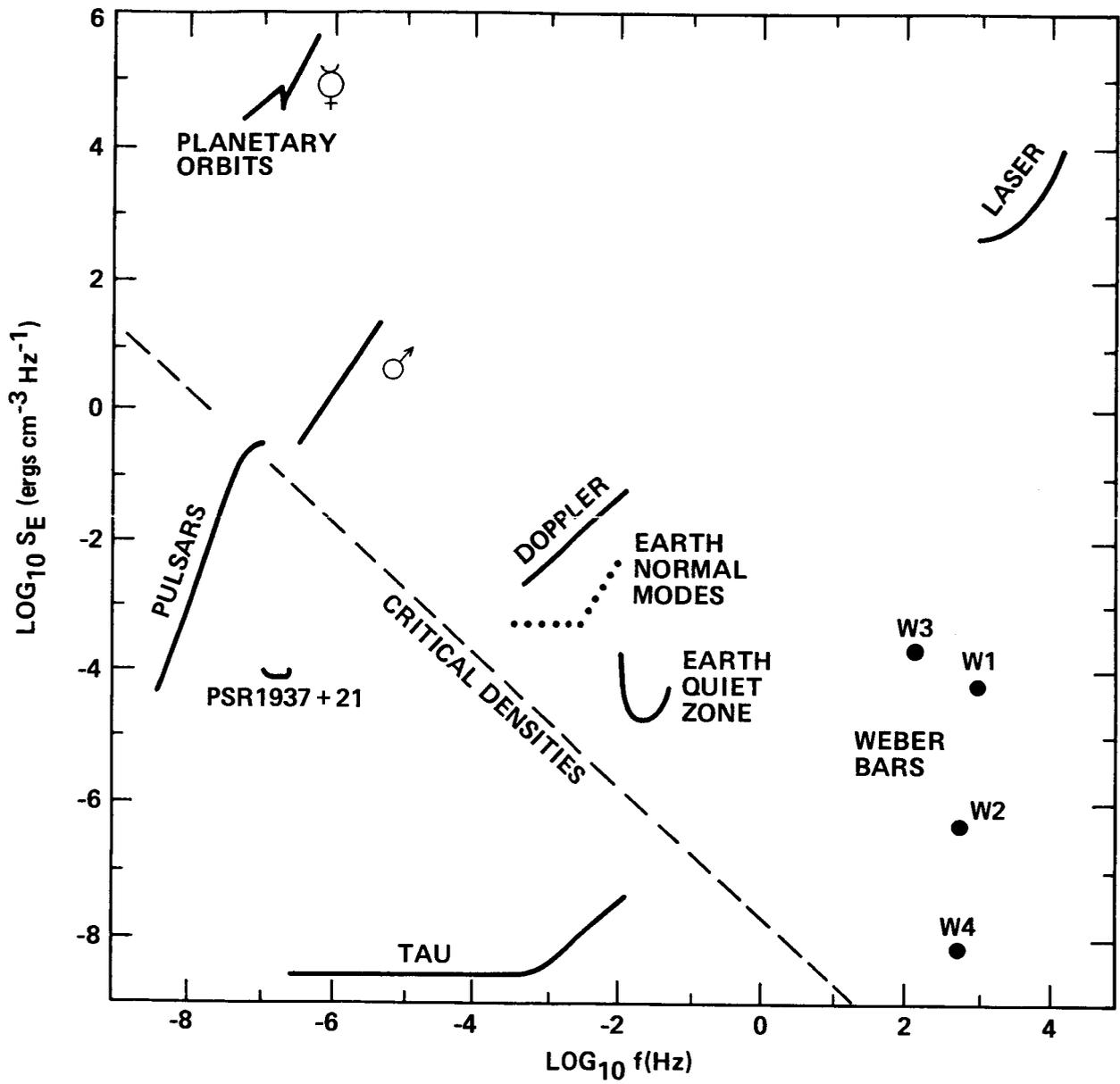
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Figure 3.     Gravity Wave Detection Limits

the limit of small accelerations, an idea that has been suggested as an alternative explanation to the Hidden Mass Theorem for explaining galactic dynamics. The breakdown of the inverse-square law would manifest itself as a special dependence in the effective gravitational constant.

$$G_{eff} = G[1 + A(r/r_0)^{2n}]$$

Where $r_0$ is the distance at which the gravitational acceleration is equal to typical galactic acceleration and A and n are determined constants.

A spacecraft at 1000 AU would attain a low enough acceleration about the sun to test this theory. With present day tracking capabilities, the power law index could be limited to $n \geq 4.3$. Planetary scale baseline probes give only $n > 1$ (Refs. 18, 19, 20, and 21).

IR background

A simple IR experiment at the range of 1-30 microns could answer very important cosmological questions such as: Is there a 10-micron background from external galaxies or quasars? Is there a 2-micron background? (Ref. 2).

3.2.4 Solar System Studies

Zodiacal light

The Helios zodiacal light experiment observed the zodiacal light intensity to vary as $r^{-2.3}$. If one assumes constant albedo and grain size distributions, then the number density of dust varies with distance as $r^{-1.3}$ (Refs. 22 and 23). It is still to be determined if either of these two parameters will vary with heliocentric distance (Ref. 24). The zodiacal light experiment on Pioneer 10/11 measured a brightness gradient of approximately $r^{-2.5}$ from 1 to 3.5 AU and no detectable signal above the starlight background beyond 4 AU (Ref. 25). Thus, the effect of the zodiacal light should be negligible beyond Jupiter's orbit. Thus, faint light observations in IR can be done much better than from Earth orbit (Ref. 26). Thermal emission from interplanetary dust dominates the 10, 25, and 60 micron background in IRAS data (Ref. 27).

## Planetary system

As TAU leaves the solar system, it could study the zodiacal light from a distance, in visible as well as IR wavelengths. The study of what a "solar system dust cloud" looks like from a distance could be used to correlate with detections of other dust clouds, such as those surrounding Vega and Beta Pictoris, which have recently been made (Ref. 26).

## Determination of the total solar system mass

By the time the spacecraft reaches 1000 AU a substantial amount of the mass of the inner Oort Cloud will be inside the orbit of TAU. A more accurate determination of the mass of the solar system than has been done to date can be done with TAU (Ref. 28).

## 3.3 Space Plasma Physics

The heliosphere can be described as a huge bubble in the interstellar gas created by the radial supersonic outflow of magnetized plasma from the sun (the solar wind) and confined by the magnetic and particle environment of the local interstellar medium. The boundary between the region of solar wind dominance and the interstellar medium is called the heliopause. The shape of the heliopause and the structure of this boundary are a function of the magnetic, dynamic and thermal pressures of the interstellar medium as well as the particle composition in this region, and their interaction with the very turbulent local magnetic environment. The boundary's characteristics, i.e., dynamic and magnetic structure as well as location, are expected to differ for each particle species. A probable model for the shape of the heliosphere is shown in Figure 4. This model was extrapolated from our present understanding of the behavior of collisionless plasmas and from our present knowledge of the heliosphere. The Pioneer and Voyager spacecraft have so far probed only the inner heliosphere, about 20% of the radial dimension of the heliosphere (Ref. 3). The radial dimension has a nominal value of about 100 AU, but estimates range from 50 to 300 AU (Ref. 3). TAU would be the first opportunity for a full complement of instruments with the proper range of sensitivity to make a cross-sectional cut of our heliosphere and sample the interaction region between the interstellar medium and the heliosphere, and provide us with a heliospheric model to be used as a base in understanding other star systems (Ref. 29).
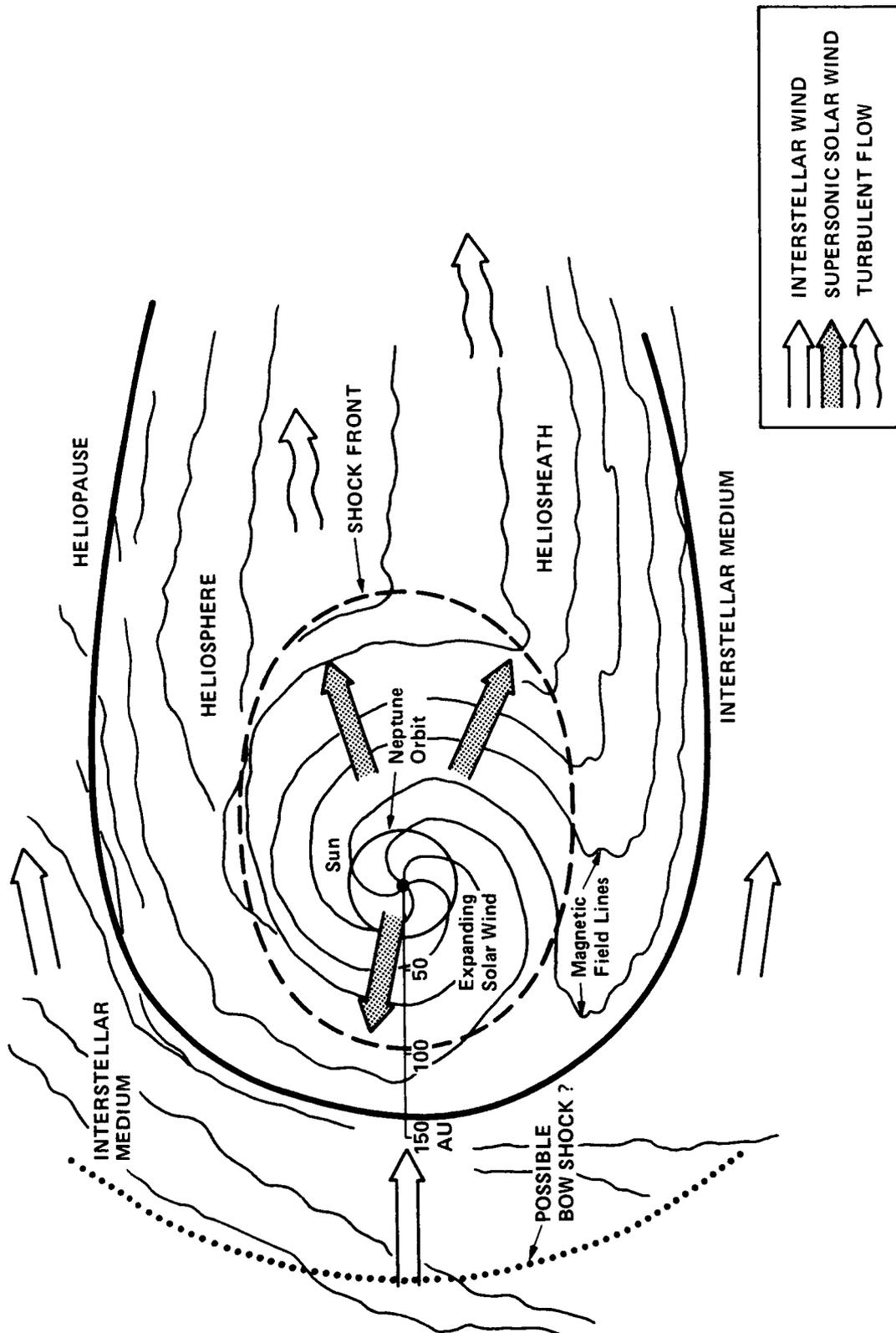
Figure 4.  Probable Model for Heliosphere

## 3.3.1 Dust

### Solar system

TAU will be able to determine the distribution of dust within the solar system, study the effect of gravitational focusing, mass and composition of the dust, and its orbital characteristics such as direction (direct vs. retrograde) and ellipticity of the orbit as well as being able to determine mass, velocity, energy, and composition of these particles. The mass and velocity will allow us to define the population of dust and the orbit of these particles in the solar system. Determination of the particle orbits is essential in distinguishing the source of the particles and in projecting the three-dimensional distribution. The velocity (speed and direction) of a particle is the discriminator between interstellar grains and solar-system-source particles.

### Heliopause

The energy and the density distribution of dust across the transition zone defined as the heliopause can be characterized by measurements taken by TAU. It will also be able to determine mass, energy, and chemical composition as well as the kinematics of particle behavior, charge exchange, and wave-particle interactions in this turbulent region.

### Interstellar medium

Instruments on TAU will be used to determine mass, energy, and chemical composition of the dust population as well as the kinematics of particle behavior of dust in the interstellar medium. Grains are expected to be on the order of $10^{-16}$ - $10^{-17}$ grams.

Dust instruments presently available, such as those used on Galileo and the Halley missions, have the capability to determine mass and velocity (speed and direction) as well as particle composition (Ref. 26).

## 3.3.2 Plasma and Energetic Particles Distribution

### Heliosphere

A TAU mission will be able to: (1) determine the composition, and characterize the energy spectrum and distribution of low energy particles in the outer reaches of the heliosphere not yet visited by other spacecraft; (2) determine regions of attenuation and energization of these particles; (3) characterize the wave-particle interactions of plasmas in the turbulent regions of the heliosphere, especially those regions dominated by the inner heliospheric shocks, and the heliopause boundary.

Interstellar medium

Measurements taken on TAU will help determine the "original" energy distribution and composition of particles of interstellar-medium origin prior to the energization and/or attenuation caused by wave-particle interactions in their traverse through the heliopause. A definition of the particle domain in the inter-stellar medium will lead to an understanding of the interaction of our star system with the galactic environment, and will help constrain models of the interstellar medium with other astro-physical conditions, i.e., star systems and jets (Ref. 30).

### 3.3.3 Low-energy Cosmic Rays

Projects on cosmic rays include attempts to: (1) determine origin, energy spectrum, and mass of cosmic rays; (2) character-ize the energy spectrum and distribution of low-energy cosmic rays; (3) characterize the interaction with and attenuation or energization of low-energy cosmic rays at the heliopause; (4) characterize the energy spectrum across the boundary; and (5) differentiate between solar sources and extra solar system sources of cosmic rays (Ref. 30).

### 3.3.4 Magnetic Field Morphology

Heliosphere/Heliopause

Determining the morphology of the magnetic field as a function of heliocentric distance will be possible with TAU. This will lead to improved magnetic field models of the heliosphere as a whole. Defining the location of the magnetic heliopause boundary, characterizing its structure, and the morphology of the regions upstream and downstream of this "boundary," inner and outer bow shocks, mass loading of field lines in the region, and magnetic instabilities caused by the unique conditions existing in the outer reaches of the heliosphere is also a projected TAU goal (Ref. 3).

Interstellar medium

TAU will determine the morphology of the galactic magnetic field, as well as the interactions with the local interstellar plasma, interstellar shocks, hydromagnetic waves and the characteristics of the local stellar winds. Determining the characteristics of the magnetic field outside of the domain of the heliosphere will help constrain models for the origin and generation of the galactic magnetic field (Ref. 30).

### 3.3.5 Plasma Waves

**Heliosphere/Heliopause**

The ability to study the plasma waves generated in the various interaction regions of the outer heliosphere, inner and outer shocks, and heliopause to determine the source of these waves, and to study the local particle-wave interactions, especially near the heliopause, is possible with a TAU mission (Ref. 30). Plasma wave emissions in the 2-3 kHz frequency range, known to be generated at planetary shocks, have also been faintly seen by Voyager from what may be the terminal shock of the heliosphere (Ref. 31).

**Interstellar medium**

Another TAU project is the study of the local plasma waves/particle interactions. TAU will also be able to sample the local charge density, and study the local (magnetohydrodynamic) MHD behavior and the microprocesses for transporting energy in the interstellar medium (Ref. 30).

# 4.0  SCIENCE INSTRUMENTATION

The scientific objectives listed in the previous section define the need for a specific complement of scientific instruments. Below is a preliminary list of the instruments that were suggested to accomplish the proposed investigations.

Strawman science payload:

  Optical/IR Telescope
  Cosmic Ray Detector
  Dust Detector
  Energetic Particle Detector
  Ion/Neutral Particle Detector
  Gamma-Ray Spectrometer
  Magnetometer
  Plasma Particle Detector
  Plasma Wave Instrument
  Ultraviolet Spectrometer
  Very Low Frequency Radio Astronomy Antenna
          a. Dipole antenna
          b. Pointable dish

Much more effort is necessary to establish the interactions of these various instruments with each other and their effect on the overall spacecraft design.

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**16. Abstract**

   A proposed mission to one thousand astronomical units (TAU) is currently being studied by the Jet Propulsion Laboratory. Launch date for a TAU mission is likely to be well into the first decade of the 21st century. Study of TAU has focused upon the technologies required to carry out this ambitious mission and the identification of preliminary scientific rationale for such a deep space flight.

   A 1-MW nuclear-powered electric propulsion (NEP) system forms the baseline method of achieving the high velocities required. A solar system escape velocity of 106 km/s is needed to propel the TAU vehicle to 1000 AU in 50 years. The NEP system must accelerate the vehicle for about 10 years before this velocity is attained because of the extremely low thrust nature of the xenon-fueled ion engines. At the end of the thrusting phase the NEP system is jettisoned to allow the TAU spacecraft and science experiments to coast out to 1000 AU.

   Another important technology for TAU is advanced optical communication systems, which are envisioned for transmitting science data to Earth. A 1-m optical telescope combined with a 10-W laser transponder can transmit 20 kbps to a 10-m Earth-orbit-based telescope from 1000 AU.

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