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Instrumentation for interstellar exploration

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Abstract

The time has arrived for designing, building, and instrumenting a spacecraft for a dedicated foray into the galactic environment surrounding our star, the sun. This region was probed in the past by remote techniques and it will be explored in situ by the NASA's planned Interstellar Probe mission. The mission will significantly advance our understanding of the nature of the local interstellar medium and explore the distant frontier of the solar system by revealing the details of the interaction between the sun and the Galaxy. This mission will also be an important practical step toward interstellar flight of the future. Reaching interstellar space in reasonable time requires high escape velocities and will likely be enabled by non-chemical propulsion such as nuclear-powered electric propulsion or solar sailing. Unusually high spacecraft velocities, enormous distances from the Sun, and non-chemical propulsion will significantly influence design of the mission, spacecraft, and scientific instrumentation. We will review measurement objectives of the first dedicated mission into interstellar space and outline constraints on the instrumentation. Measurement of particles, fields, and dust in the interstellar medium will be complemented by search for complex organic molecules and remote sensing capabilities in various spectral bands. A "look" back at our solar system will also be a glimpse of what a truly-interstellar mission of the distant future would encounter in approaching a target star. The instrumentation for interstellar exploration presents numerous challenges. Mass, telemetry, and power constraints would place a premium on miniaturization and autonomy. There are, however, physical limits on how small the sensors could be. New instrument concepts may be required to achieve the desired measurement capabilities under the stringent constraints of a realistic interstellar mission.

Keywords: Interstellar exploration; Interstellar spacecraft; Instrumentation; Interstellar probe mission

1. First step into interstellar space

Our first step into the galactic environment in the sun's vicinity will necessarily be modest. The first spacecraft specifically designed for the interstellar study will concentrate on exploring the distant frontier of the solar system and the galactic region immediately beyond. Much of the information on this region has been obtained either remotely or by examining interstellar matter that penetrated deeply into the heliosphere. The derived properties of the local interstellar medium (LISM) are averaged over large, "astronomical" distances in the former case and the inflowing interstellar matter is disturbed and filtered by the heliospheric interface region in the latter.

The primary goal of the first interstellar mission is to reach the unperturbed, "virgin" interstellar medium and to examine its properties in situ. The physics and state of the LISM are not known in many important details (Cox and Reynolds, 1987; Frisch, 1995; Breitschwerdt, 1996). Fig. 1 shows a schematic of the sun's frontier and galactic neighborhood. The sun moves with respect to the surrounding interstellar medium with the velocity 26 km/s, or ~5 AU/yr. This motion is described as the interstellar wind, with the wind direction close to the ecliptic plane. The heliosphere is the region where the sun controls the state and behavior of the plasma environment (Parker, 1963; Dessler, 1967; Axford, 1972). Experimental data on the heliosphere interaction with the LISM and on the properties of the region of the heliospheric interface are scarce, mostly indirect, and

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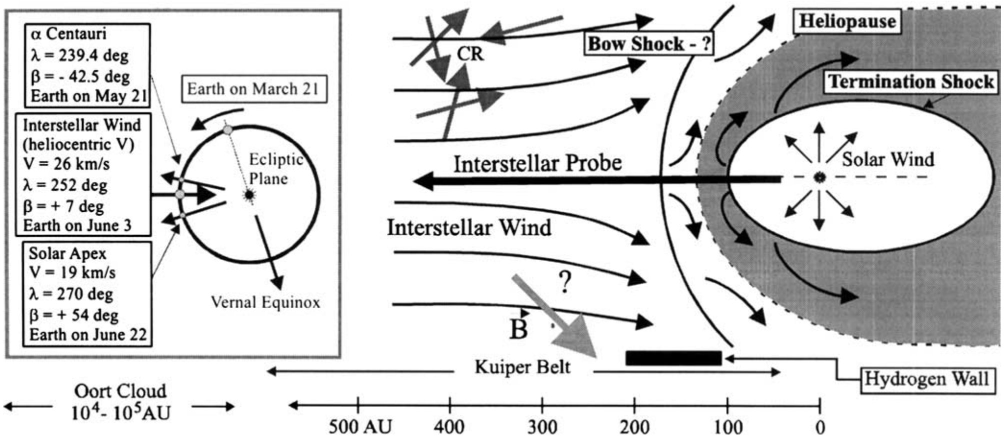

Fig. 1. Sun's galactic neighborhood (right). Box (left) shows important direction in the ecliptic plane (interstellar wind vector, apex, α-Centauri).

often ambiguous. A self-consistent model of the heliosphere has yet to be built and many aspects of the interaction are not understood. Therefore, the second major goal of the first interstellar mission is to explore the solar system frontier.

Voyager 1 is headed in the approximately upwind (interstellar wind) direction. The spacecraft was at 86 AU from the sun in the fall of 2002 and it did not reach the termination shock yet. The supersonic solar wind flow is believed to undergo a shock transition to a hot subsonic flow (the hatched region in Fig. 1), which carries the shocked solar wind plasma to the heliospheric tail. The tail would eventually mix with the surrounding interstellar gas at distances of 1000–2000 AU. It is anticipated that Voyager 1 will cross the shock, likely somewhere within 110 AU from the sun. The spacecraft will continue to operate until the year 2020 by which time it may even reach the heliopause (Fig. 1), the boundary separating the solar and galactic plasmas.

There are no direct experimental data on the size and shape of the heliosphere. The interstellar wind, solar wind latitudinal (heliolatitude) variations, and interstellar magnetic field make the heliosphere essentially three-dimensional (3-D) and asymmetric. While the LISM velocity vector is well known (e.g., Lallement et al., 1993; Witte et al., 1996) and the solar wind asymmetry has been unambiguously revealed by Ulysses (McComas et al., 1998; Neugebauer, 1999), the interstellar magnetic field vector is largely unknown. Other major uncertainties in the LISM properties include number densities and ionization states of the dominating species, hydrogen and helium, and abundance of low-energy galactic cosmic rays. In addition, it is not known whether the flow of interstellar plasma is,supersonic or subsonic and whether the bow shock (Fig. 1) is formed (e.g., Baranov, 1990). We also know very little about the heliopause, with the direct experimental data next to non-existent (Suess, 1990).

Many fundamental assumptions of our present concept of the global heliosphere have never been directly verified experimentally, including whether the solar wind expansion is terminated by the shock and whether the shock is strong or weak. The heliosphere is a complicated 3-D non-stationary phenomenon where the solar wind and galactic plasmas, neutral interstellar gas, magnetic field, and anomalous and galactic cosmic rays play prominent dynamic roles. The lack of the direct experimental data and the resulting uncertainties in understanding of fundamental processes of the sun–LISM interaction severely limit our ability to develop a self-consistent concept of the heliosphere. Exploring in situ the nearby galactic environment and the region of the solar system frontier is thus an essential, logical, and unavoidable step in our quest for understanding our star, its interaction with the Galaxy, and laying out the foundation for the truly interstellar flight of the distant future.

Voyager 1 is anticipated to reach the termination shock and establish its properties in one point-direction. The new remote technique of heliosphere imaging in fluxes of energetic neutral atoms (ENAs) will establish the nature of the termination shock and reveal the asymmetry of the heliosphere (Gruntman et al., 2001; McComas et al., 2003). The heliopause will also be mapped remotely in extreme ultraviolet (Gruntman and Fahr, 2000; Gruntman, 2001a,b). The in situ measurements by Voyager 1 and new remote techniques will significantly advance our understanding of the global 3-D heliosphere. These advances cannot substitute for, however, a dedicated interstellar probe that will cross the entire heliospheric interaction region and explore in situ the unperturbed nearby galactic medium. The ground truth measurements by an interstellar mission will verify our fundamental concepts and, together with the remote techniques,open a way for a comprehensive understanding of the solar system frontier.

2. Spacecraft velocity and propulsion

A mission to interstellar space was studied by NASA for 30+ years (e.g., Jaffe et al., 1980; Nock, 1987; Mewaldt et al., 1995). The latest study of such a mission, called the *Interstellar Probe*, reviewed science and instrumentation requirements for the first step in interstellar exploration and confirmed that the emerging propulsion technologies would enable such a realistic mission at an acceptable cost (Mewaldt and Liewer, 1999). The details of this latest study are presented by Liewer et al. (2001) and Mewaldt and Liewer (2001, 2004).

The most serious challenge for the first interstellar mission is reaching the unperturbed interstellar medium in the shortest possible time. Propulsion technology essentially limits escape velocities of spacecraft leaving the solar system. Consequently, it is critical to minimize the distance that the spacecraft has to cover. The theoretical models predict the shortest distance to the termination shock and the heliopause in the upwind direction. For example, the heliopause in the sidewind direction may be as much as 50% farther away from the sun than in the upwind direction. Therefore, the upwind direction is preferred for the first mission to interstellar medium.

How far should the spacecraft go in order to reach the unperturbed galactic environment? The solar wind plasma produces ENAs (e.g., Gruntman, 1994) that would deeply penetrate interstellar medium. These ENAs undergo charge exchange on interstellar plasma ions, thus transferring energy and momentum to the incoming plasma flow wind. The curved interstellar wind streamlines illustrate this effect in Fig. 1. Fig. 2 shows a typical simulated heliocentric dependence of the temperature of the approaching supersonic interstellar wind plasma (Baranov and Malama, 1993). Even a supersonic interstellar wind would "learn" about the presence of an obstacle, the heliosphere, ahead before undergoing through a bow shock. This disturbing effect of the solar ENAs was predicted by Gruntman (1982) and was later confirmed by detailed calculations by Baranov and Malama (1993) and others (e.g., Zank, 1999). Galactic cosmic rays would also be disturbed by the presence of the heliosphere. It is believed that the unperturbed interstellar medium can be found at 350–400 AU from the sun (Mewaldt and Liewer, 2001), which is the desired distance for the first interstellar mission. The minimal distance for observing gravitational focusing of the electromagnetic radiation by the sun is farther away at 550 AU (Maccone, 1997) and the Oort Cloud is even at much greater distances (Fig. 1).

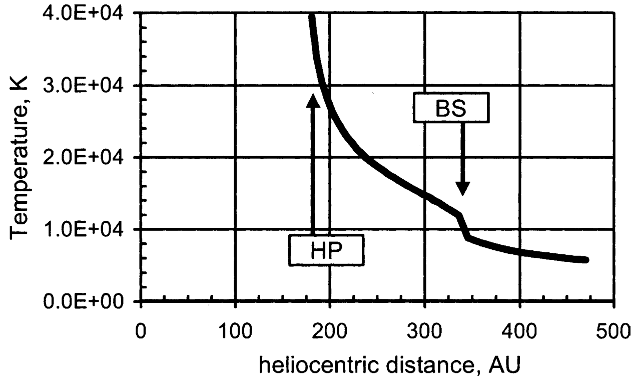

Fig. 2. Computer simulations of temperature of the interstellar wind plasma. The arrows indicate positions of the heliopause (HP) and bow shock (BS).

The desire to reach the 400-AU destination within the half of the lifespan of a typical active career of a scientist and engineer, that is within 20 years, is reasonable and understandable. Consequently, one has to require the escape velocity of 15–20 AU/yr for an interstellar mission. Fig. 3 shows the relation between velocities in the units of km/s and AU/yr. We will consider in this article a mission with the nominal escape velocity 75 km/s or 15.8 AU/yr. This velocity is close to the 14-AU/yr velocity adopted by Mewaldt and Liewer (1999, 2001).

Traditional chemical rocket propulsion is not promising for achieving such velocities. The escape velocity of 75 km/s requires a spacecraft with the velocity of 86 km/s at 1 AU. Therefore, in addition to delta-V necessary to escape earth's gravity, the spacecraft should acquire extra 56 km/s. This velocity increment alone translates into the rocket mass ratio 340,000 for the most efficient chemical (hydrogen–oxygen) propulsion systems with specific impulse 450 s. Mission duration constraints eliminate the possibility of multiple planetary gravity-assist.The desired enormous mass ratio is clearly unrealistic and alternative propulsion technologies are required. Such enabling technologies include nuclear electric propulsion and solar sails, both of which could be brought to the required technology readiness level within several years of the dedicated effort.

The technology of nuclear fission power systems is mature (Sackheim et al., 2001) and its implementation in space flight was blocked by the obstacles other than those of technological merit, efficiency, or safety. Recent political changes in the United States and the emerging

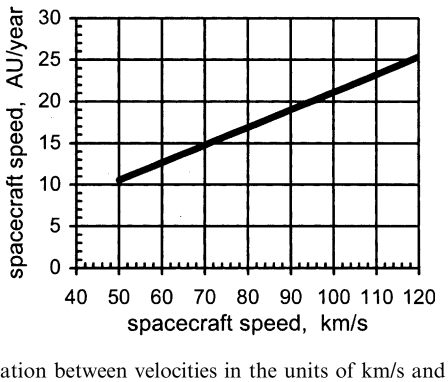

Fig. 3. Relation between velocities in the units of km/s and AU/year.

advocacy within NASA may finally lead to realization of nuclear electric propulsion. The recently gained experience in operation of electric thrusters for a long period of time enhances the confidence in the technical validity of the approach. A powerful nuclear electric propulsion system may seriously disturb the immediate environment surrounding the spacecraft. The possible effects on the surrounding plasma, the latter to be studied in great detail by the interstellar mission, and on the sensitive science instrumentation require accurate quantification. (The desired measurements of magnetic fields and plasma and radio waves would require an electromagnetically clean spacecraft.) If the expected disturbances are unacceptable, then the interstellar mission will jettison the reactor at some distance from the sun, say at 50 AU, and proceed powered by a small radio-isotope thermal generator (RTG).

The technology of solar sails is rapidly approaching maturity (Leipold, 2001; Liewer et al., 2001) and will enable a variety of space missions, especially in the sun's vicinity. The recent Interstellar Probe study (Liewer et al., 2001) assumes a solar sail with a 200-m radius and total areal density 1 g/m^2. The spacecraft would first approach the sun to a distance of ~0.25 AU and then, after flipping the sail, accelerate on the escape trajectory. A large solar sail would disturb the immediate plasma environment around the spacecraft and make many scientific measurements impossible. The mission scenario correspondingly calls for the sail to be jettisoned at 5 AU, with the spacecraft continuing on its journey to interstellar medium powered by an RTG.

3. Measurement objectives

A mission to interstellar space is unique and should focus on the measurements that cannot be performed anywhere else in the solar system. Consequently, there are three types of measurements:

1. In situ exploration of the unperturbed interstellar medium.
2. In situ exploration of the region of the interaction between the heliosphere and galactic environment.
3. Remote observations at large heliocentric distances.

The range of the parameters to be measured—number densities, effective temperatures, particle and photon fluxes, and plasma wave intensities—would vary by orders of magnitude during the mission. Fig. 4 illustrates typical expected variations of the plasma number density along the spacecraft trajectory (Baranov and Malama, 1993). In another example, the magnetic field is expected first to drop from about 1 nT (1 nT = 1 $\gamma = 10^{-5}$ gauss) in the inner heliosphere to 0.01 nT at the termination shock, then climb to 1 nT at the heliopause, and finally gradually decrease to the expected interstellar level of 0.1 nT. Measurements of such a low magnetic field would require sensors deployed on the booms extending more than 30 m. A dipole antenna for measuring plasma and radio waves would exceed 100 m tip to tip.

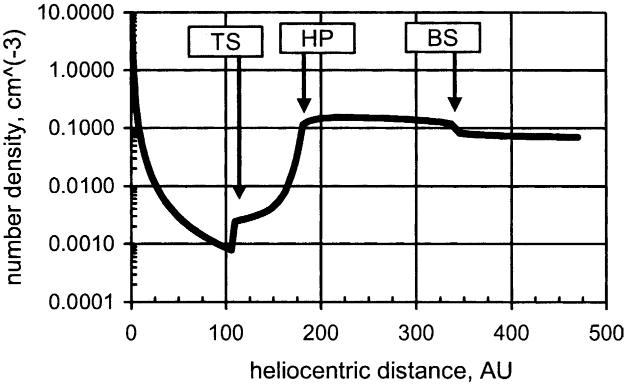

Fig. 4. Heliopause plasma "moat" surrounding the sun: a typical expected heliocentric dependence of the plasma number density in the upwind direction. The arrows indicate the positions of the termination shock (TS), heliopause (HP), and bow shock (BS).

3.1. In situ study of interstellar medium

The primary goal of the first interstellar mission is to reach the unperturbed interstellar medium and to examine its properties in situ. Key measurement objectives include determination of isotopic and elemental composition of interstellar matter in gaseous and dust forms, establishing the ionizations state of various constituents of interstellar gas, and characterization of interstellar magnetic field and galactic cosmic rays. A search for organic matter in interstellar space is an important mission objective.

Interstellar plasma cannot penetrate the heliopause, flows around it, and is thus inaccessible directly in the solar system. Interstellar neutral gas reaches the inner heliosphere but its components are often filtered and disturbed by the passage through the heliospheric interface, which introduces uncertainties in interpretation of observations. Large interstellar dust grains, >10 μm, are measured in the inner heliosphere but small (<0.1 μm) grains are prevented from entering the solar system by the solar wind magnetic field. The intermediate-size grains, 0.1–2.0 μm, are also subjected to significant solar radiation pressure. In addition, interstellar dust grains penetrating deep into the heliosphere are heated by the solar radiation, which may destroy tale telling organic molecules. Thus, the small interstellar grains unmodified by the sun can only be examined in interstellar medium.

The interstellar mission will cross the Edgeworth–Kuiper disk, or belt, of the "debris" of the primordial solar nebula. The disk is believed to be a source of the low-inclination short-period comets in the solar system.

The collisions of the Edgeworth–Kuiper belt bodies efficiently produce dust grains (e.g., Stern, 1995). In spite of the Poynting-Robertson effect, many of these dust particles are prevented from reaching the inner heliosphere and ejected from the solar system by the giant planets (Liou et al., 1996). The interstellar mission will open a way to directly probe this important dust population.

Low-energy (<200 MeV/nucleon) galactic cosmic rays are similarly excluded from the inner heliosphere and can be measured only on an interstellar spacecraft. The cosmic ray fluxes increase with the decreasing energy. Low-energy cosmic rays are thus believed to be most abundant, and the inaccessibility of such cosmic rays from the inner heliosphere prevents determining their contribution to the energy density in the galaxy.

The extreme ultraviolet and soft-X-ray radiation would efficiently ionize organic molecules present in the LISM. Such ions are consequently excluded from entering the heliosphere. We do not know whether amino acids exist in interstellar medium, while polycyclic aromatic hydrocarbons (PAH) are believed to be most abundant. Search for and detection and identification of complex organic molecules are a challenging goal (e.g., Mewaldt and Liewer, 1999) of the first mission to interstellar space.

3.2. In situ study of the heliospheric interface

In situ examination of particles, fields, waves, and processes while crossing the entire heliospheric interface region is a major goal of the interstellar mission. These are the ground truth measurements that will test our fundamental concepts of the heliosphere and its interaction with the nearby galactic medium. Together with the emerging remote techniques, the in situ measurements will open a way for a comprehensive understanding of the 3-D solar system frontier.

The experimental objectives of the mission include characterization of the termination shock and bow shock; measuring the variations across the interaction region of the solar wind plasma, solar wind pickup ions, suprathermal ions, interstellar plasma, and solar and interstellar magnetic fields. The mission will reveal details of particle acceleration at the shock and establish energy spectra of anomalous and galactic cosmic rays. The measurements will help in quantifying filtering of the interstellar neutrals. Recording of plasma waves along the spacecraft trajectory will identify the origin of the enigmatic low-frequency heliospheric radio emissions (Kurth and Gurnett, 2001).

Combined in situ measurements of charged and neutral particles with the measurements of interstellar gas glow at hydrogen Lyman-α (121.6 nm) will determine the structure of the hydrogen wall (Fig. 5).

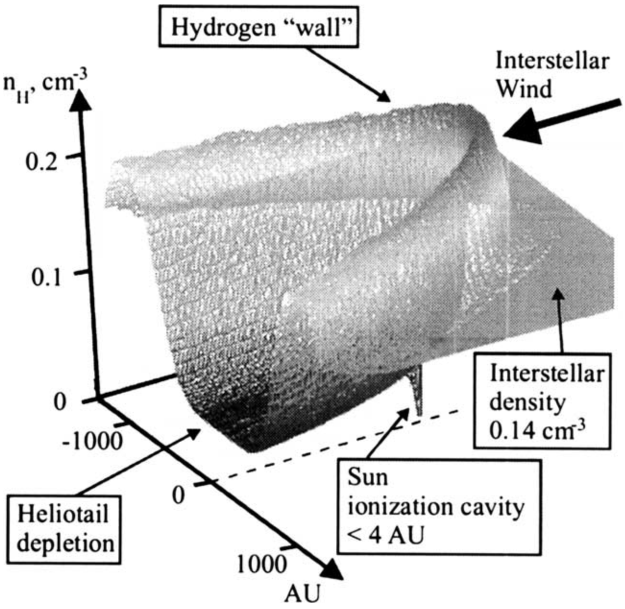

Fig. 5. Distribution of interstellar atomic hydrogen. The density enhancement, called the "hydrogen wall," is the effect of the plasma-neutral gas charge-exchange coupling. Calculations of Baranov and Malama (1993).

3.3. Remote observations

The third category of experiments will take advantage of large heliocentric distances of the spacecraft for remote obsertvations. Measurements of the interstellar hydrogen glow in H Lyman-α will allow one to obtain the absolute number density of neutral hydrogen atoms in the LISM. (Such measurements could be performed by a simple broadband photometer pointed in the approximate anti-solar direction.) Multiple scattering of the solar Lyman-α radiation at large heliocentric distances determines a heliocentric dependence of the glow. The glow intensity would thus depend on the effective optical depth of the hydrogen gas rather than on the absolute distance from the sun, opening a way for establishing the number density of interstellar hydrogen independent of the sensor absolute calibration. Another sensor, pointed at the sun, can measure attenuation of the solar Lyman-α, as the spacecraft leaves the solar system, and it will also provide information on the heliocentric distribution of interstellar hydrogen and its absolute number density independent of the absolute calibration.

Measurements of Lyman-α radiation at 300–400 AU from the sun would also allow one, for the first time, to obtain the galactic background in Lyman-α. Observation of the galactic background is impossible from the inner heliosphere because of the exceptionally bright glow of interstellar hydrogen inflowing into the heliosphere. The simulations predict that the scattering of the solar radiation on interstellar gas, or the glow, would contribute less than 5 Rayleigh (1 Rayleigh = $10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}) for an anti-solar direction of observation at 400 AU. An observed excess intensity could therefore be explained by at this time the unknown galactic background. The upwind direction of the interstellar spacecraft trajectory is 18° off the direction toward the galactic center and 83° off from the direction toward the Galactic North pole. Therefore it would be possible to determine the anisotropy of the galactic Lyman-α background by offsetting a Lyman-α sensor from the spin axis on a spinning sun-pointed interstellar spacecraft.

Similarly to the galactic Lyman-α radiation background, the cosmic infrared radiation background cannot be observed from the inner heliosphere because of the bright emissions of the zodiacal dust. An infrared sensor on the interstellar spacecraft would be able to separate and determine the contributions to the observed infrared intensities by interstellar dust and by cosmic background.

The interstellar mission will provide a unique platform for a stereoscopic observation of the heliospheric interface region. The region of the heliospheric sheath is a source of the heliospheric ENAs that will be imaged from the inner heliosphere (Gruntman, 1997; Gruntman et al., 2001; McComas et al., 2003). Integration along the line of sight is a fundamental limitation of imaging, which compresses an essentially 3-D object into a 2-D image. Stereoscopic imaging can therefore significantly reduce the ambiguity of image interpretation. In case of the heliosphere, its sheer size makes such stereoscopic imaging possible only from an interstellar platform. The interstellar mission would offer a unique opportunity to complement heliosphere imaging (Gruntman et al., 2001) from 1 AU, or from another point in the inner heliosphere, by ENA images from 100–200 AU. Fig. 6 demonstrates how ENA sensors pointed at 45° and 90° with respect to the upwind spacecraft trajectory would "slice" through the heliosheath providing information about its exact shape and the plasma properties.

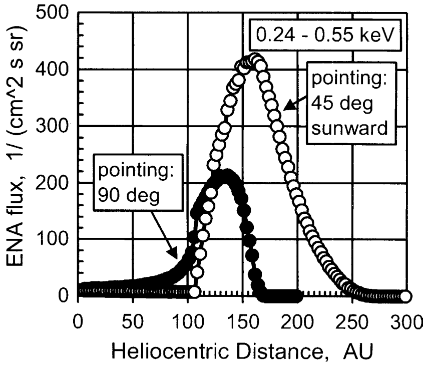

Fig. 6. Typical ENA flux as would be observed by a spacecraft headed in the upwind direction in the 0.24–0.55 keV energy range. The sensors are pointed 90° and 45° (tilted sunward) with respect to the spacecraft trajectory.

Traditional optical remote sensing instruments can also take advantage of large heliocentric distances. The interstellar spacecraft would pass through the Edgeworth–Kuiper Belt and can survey the distribution of the Kuiper objects along its trajectory. The spacecraft would also offer a unique platform for optical parallax measurements from several hundreds AU from the sun.

4. Spacecraft environment

The exceptionally high speed of the interstellar spacecraft would result in rather unusual experimental conditions, for example, in a large Doppler effect. The atomic hydrogen Lyman-α 1216 Å (121.6 nm) line would be Doppler shifted by 0.3 Å (0.03 nm) and the sodium lines at 5890 Å (589 nm) would be Doppler shifted by ~1.5 Å (0.15 nm). The spacecraft velocity is nominally pointed in the upwind (interstellar wind) direction. The interstellar wind approaches the sum with the speed 25 km/s or 5.3 AU/yr. The relative velocity of interstellar matter with respect to the spacecraft would thus be 100 km/s and the corresponding energy 52 eV/nucleon. Thus, an oxygen atom or ion would have the energy 830 eV. The corresponding electron kinetic energy is 0.03 eV.

This high energy of plasma ions would make the conditions for search, detection, and identification of organic molecules rather difficult. Two most common PAH molecules are coronene ($C_{24}H_{12}$) and hexabenzocoronene ($C_{48}H_{18}$). The molecular weights of these two molecules are 300 amu and 594 amu and their corresponding energies with respect to the spacecraft would be 15.5 and 30.9 keV. Although these energies could be within the energy ranges of the instruments for study of suprathermal ions, the molecules cannot be analyzed with the thin foil-based time-of-flight technique because their energy per nucleon is insufficient for foil penetration. On the other hand, the molecule energy is too high for being captured and adsorbed on the surface without having its molecular bonds disrupted.

The properties of the plasma to be examined will be changing dramatically throughout the mission. Fig. 4 shows typical expected number densities of the plasma along the trajectory in the upwind direction. Fig. 7 shows the corresponding plasma Debye length varying from two meters to about 1 km.

The solar wind consists of 95% of protons, 5% of alpha particles, and many other trace elements. The population of the pick up protons with a distinctly different velocity distribution function would grow as the solar wind propagates toward the solar system frontier and may reach 25% of the solar wind protons by the termination shock. The interstellar medium plasma

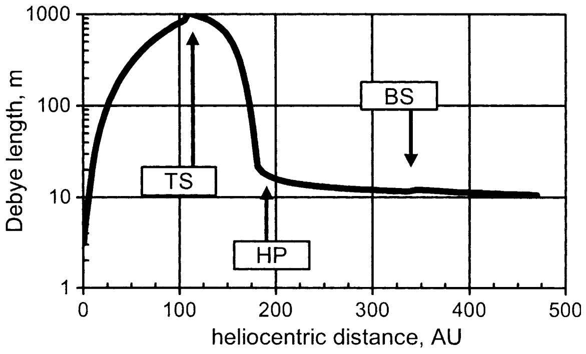

Fig. 7. Typical Debye length of plasma in the upwind direction.

consists of approximately 90% of hydrogen, 10% of helium, and many other trace elements. The interstellar gas is partially ionized, but it is not in thermodynamic equilibrium and could even be in a non-stationary ionization state. Populations of suprathermal ions and electrons as well as magnetic field will also vary dramatically along the spacecraft trajectory.

5. Measurement concepts, instruments, and challenges

The main types of measurements on the first interstellar mission are reviewed by Mewaldt and Liewer (1999, 2001). The possible science payload includes instruments measuring magnetic fields; plasma and radio waves; solar wind and interstellar plasma ions and electrons; pickup ion velocity distributions; pickup ion composition; composition of interstellar plasma and interstellar neutral atoms; properties of suprathermal ions and electrons; ENA fluxes; cosmic ray ions, electrons, and positrons; anomalous cosmic rays; mass distribution of dust grains and their composition; Lyman-α radiation intensity; infrared radiation intensity; complex organic molecules; and possibly some other.

The instrumentation for interstellar exploration presents numerous challenges. The unusually long mission duration and high cost of the Deep Space Network resources would call for the high degree of autonomy of operation of the spacecraft and instrumentation. Mass, telemetry, and power constraints would place a premium on instrument miniaturization. There are, however, physical limits on how small the sensors could be. An accumulation of the statistically significant number of counts in particle instruments would require certain effective geometrical factors and corresponding effective areas and solid angles of the instruments.

The first interstellar mission spacecraft will most likely be a sun-pointed spinner allowing sampling of the velocity distributions of particles and measuring fields by the instruments without mechanical motion with respect to the spacecraft. In addition, a spinning spacecraft would allow remote sensing instruments to scan the sky. The high spacecraft speed would result in special requirements to the instrumentation.

Consider, for example, an instrument for analysis and detection of neutral interstellar gas. Such an instrument has to capture the incoming gas flow which would be contained within an angle determined by the thermal velocity of atoms in the LISM. For a typical LISM temperature of 7500 K, such important interstellar gas species as atomic oxygen and neon would thus be confined within the angle of 3°. A straightforward arrangement would be to boresight the instrument in the direction of the spacecraft velocity vector. It is not inconceivable, however,that an interstellar spacecraft propelled by the solar sail would be deployed on the escaping trajectory several degrees off the nominal upwind direction. The incoming neutral gas may thus "miss" the instrument field-of-view.

The challenges to the instrumentation for an interstellar mission can be roughly divided into the two categories. The first category calls for improving the existing instrumental concepts by better, smaller, lighter, less power consuming, and more capable components. For example, a development of solid-state detectors allowing direct and efficient counting individual particles (ions or neutrals) with the energies down to one hundred eV, or even lower, would be a major advancement eliminating the necessity of particle detectors on the basis of secondary electron emission. The latter detectors, especially microchannel plates, require high voltage, are fragile and sensitive to the vacuum conditions and may degrade due to outgassing contamination. Such solid-state detectors would operate at much lower voltages and would not require particle pre-acceleration. A wide range of instruments for analysis, identification, and detection of ion, electrons, and ENAs would benefit from low-energy solid-state particle detectors.

The second category of challenges calls for development of new instrumentation concepts. It is not clear, for example, what is the best way of analyzing complex organic molecules in interstellar gas and plasma. The high energy of such molecules, 52 eV/nucleon, would likely destroy their molecular bonds (complicating identification) when captured on a surface for a subsequent analysis. On the other hand, the molecule velocity and energy would not be sufficient for analysis in conventional thin foil-based time-of-flight instruments.

Interpretation of dust grain measurements and search for traces of organic matter in the grains would also be complicated by an exceptionally high speed of grains with respect to the spacecraft. The grain velocities would be even higher than those at the Comet Halley flybys by the Giotto and Vega spacecraft. The 100 km/s relative velocity also significantly exceeds the velocities that can be achieved in laboratory particle accelerators. Therefore, interpretation of the measurements would essentially rely on the theoretical predictions of the effect of high-velocity impact without verification in laboratory experiments. Complex organic molecules, carried by the grains, will also be entirely dissociated and fragments ionized in the impact, as the rest of the grain material.

New smart instrument concepts, combining autonomy, elements of intelligence, and clever design, are required to achieve the desired measurement capabilities under the stringent constraints of a realistic interstellar mission. It is important to look for the untraditional ways of obtaining information on the parameters of the plasma, dust, and fields. For example, the spacecraft effective area would certainly be orders of magnitude larger than the sensitive area of a dedicated dust detector. Dust particles bombarding the spacecraft may thus be detected and statistically characterized by measuring the effects of the hot plasma produced by such impacts, as was demonstrated by Gurnett et al. (1983). The whole spacecraft could serve as one large detector of certain properties and processes in space.

Precise tracking of the interstellar spacecraft may also open a way for study of fundamental physical effects. Some observed acceleration of the Pioneer spacecraft has so far not been accounted for in spite of a significant effort (Anderson et al., 2002). A number of hypothetical explanations were proposed, invoking dark matter, quantum cosmology, and other fundamental physical concepts and theories. Precise tracking of the spacecraft may even measure masses of some bodies in the Edgeworth–Kuiper belt. The interstellar mission would be an excellent platform for precision celestial mechanical experiments that must be planned and designed in advance to take the full advantage of the unique mission capabilities.

6. Look back

As our first interstellar spacecraft leaves the solar system, a "look back" would provide us with an unusual view of our home stellar system, a view from the outside. A view back will provide a unique opportunity for a global study of the heliosphere, a vast essentially 3-D region governed by the sun. This view back would also be a glimpse of what a truly interstellar mission of the distant future would encounter in approaching a target star. A combination of obtaining images from two vantage points, one from the outside of a stellar system and one from inside, would allow the characterization of an astrosphere.

The expected emissions in the extreme ultraviolet are too weak (Gruntman, 2001a,b) to be effectively detected in the presence of the bright star. Imaging in the fluxes of ENAs would offer a much better opportunity (Gruntman et al., 2001). Unfortunately, the preferred direction of the interstellar mission in the upwind direction is unfavorable for observing the heliosphere in ENAs from the outside. Most of the hot plasma would be moving from the observer, except in a small (stagnation) region in the immediate nose of the heliosphere, thus reducing the intensity and energy of the ENAs reaching the observer. Approaching another star from a different, non-upwind direction would present an excellent vantage point of observing the structure of the astrosphere.

The neutral solar wind (Gruntman, 1994) will, however, be prominent in case of the Interstellar Probe mission and measured by the spacecraft leaving the solar system. When approaching another star, one would first see first this flux of the neutral stellar wind, thus determining the main properties of the stellar wind. Only later the starship would enter the region of the stellar wind itself, the astrosphere, and explore it directly.

The Sun will remain the brightest object in the sky for the first interstellar mission. Even from the distance of 400 AU the sun will have an apparent visual magnitude of $m = -13.7$, immensely brighter than the brightest star of our skies, Sirius ($m = -1.46$). Only when the Interstellar Probe reaches ~100,000 AU (0.5 pc or 1.6 l.y.) from the sun in six thousand years, only then our sun will surrender its supremacy as the brightest star of the sky.

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