DIRECT INTERSTELLAR ATOM AND HELIOSPHERIC-INTERFACE ENA DETECTION ON INTERSTELLAR PROBE - MISSION TO THE SOLAR SYSTEM FRONTIER

Report No. 101

MICHAEL GRUNTMAN

October, 1990

SPACE SCIENCES CENTER
University of Southern California
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I. AIM OF THE WORK

The cohabitation of the Sun and the surrounding interstellar medium results in the interaction of two different worlds of a common genesis: the local, stellar, solar and the relatively universal, galactic, interstellar. The "solar world" is highly dynamic, unstable and far from equilibrium, and the interstellar one is, by comparison, solidly tranquille. On the macroscopic scale the major manifestation of the encounter of these worlds is a build up of the heliosphere. Direct experimental data on this interaction are quite limited. The heliosphere provides a unique opportunity to study in detail the only accessible example of a commonplace astrophysical phenomenon - the formation of an astrosphere. Not less important and perhaps more intriguing and challenging is the idea to explore *in situ* the local interstellar space in its original state, i.e. in the areas unaffected by the presence of the Sun.

The interest to study the heliosphere and the local interstellar medium has obviously increased during the last decade. This led to the highly successful **Ist COSPAR Colloquium on Physics of the Outer Heliosphere** held in the fall, 1989, in Poland and, later, to a workshop in Virginia devoted to the exciting future mission - to send a specially dedicated spacecraft to interstellar space. The latter workshop, held in March, 1990 at Ballston,VA, defined the scientific rationale and requirements for an Interstellar Probe Mission. As stated in the Workshop summary (*The Interstellar Probe, 1990*) and collected papers (*Interstellar Probe Workshop. Collected papers, 1990*), the spacecraft will cross the solar wind termination shock and make a significant penetration into interstellar space. The principal focus of the Interstellar Probe will be *in situ* particle and fields measurements at the boundary of the heliosphere and in local interstellar space. The space probe will move with a velocity of **10 AU/year (50 km/s)** in the direction of the nose of heliosphere, with a goal of reaching at least **200 AU**. Possible time for the mission - years **2000-2020**.

The measurement of neutral atoms is one of the key, indispensable elements of such a mission. The difficulty of measuring interstellar neutrals was emphasized in the summary of the workshop *The Interstellar Probe, 1990*. It was stated there that "with the exception of the instrument to measure interstellar neutrals, all the instruments in the strawman payload are based on the existing technology" and the "design of an instrument [for neutrals] will be a challenge."

The idea of this work is to offer a way to meet this challenge with the focus on the Interstellar Probe mission.

One possible approach to study neutrals, discussed at the Workshop (*Mitchell and McEntire, 1990*), is based on the ideas of the instrument to measure directly the flux of interstellar helium atoms developed by Max-Planck-Institut fuer Aeronomie, Lindau (*Rosenbauer et al, 1983; 1984*) for Ulysses mission. It was suggested (*Mitchell and McEntire, 1990*), that EUV background photons, which are the major obstacle for the measurements of such a kind, may be removed by implementing of additional rotating chopper wheel or shutter which select also desirable velocity range of neutrals.

The aim of this work is to propose an alternative package of instruments (without mechanically moving parts) which will measure characteristics of neutral atoms during Interstellar Probe Mission. This package consists of three separate instruments: i) the NAD-1 (NAD stands for Neutral Atom Detector) to measure interstellar helium; ii) the NAD-2 to measure interstellar hydrogen; and, finally, iii) the NAD-3 to measure energetic neutral atoms (ENAs) which are emitted from the heliosphere interface region. All utilized experimental approaches are based on the techniques which major elements have been proved either in space flight or in the laboratory.

Author deliberately included in references the (excessively) large number of his own publications in order to give the time frame for the development of the presented ideas.

II. WHAT KIND OF NEUTRAL ATOM FLUXES CAN BE EXPECTED BY INTERSTELLAR PROBE

2.1 Two types of neutral atoms

All neutrals that will be met by Intestellar Probe can be divided into two groups according to their origin: interstellar ("primary") atoms of interstellar gas and more energetic ("secondary") atoms born in the interaction (charge exchange process) of interstellar gas with the solar wind in heliospheric interface region.

The Interstellar Probe, which is spin stabilized, moves towards the nose of heliosphere with the velocity of **10 AU/year (50 km/s)** (fig.1). Neutral interstellar gas is expected to move with the velocity of **20 km/s** relative to the Sun. Interstellar gas is believed to consist mostly of hydrogen ($\mathbf{n_H = 0.1\ cm^{-3}}$) and helium ($\mathbf{n_{He} = 0.01\ cm^{-3}}$) atoms with traces of other elements. Expected temperature of interstellar gas is $\mathbf{10^4\ K}$. Fluxes of interstellar helium and hydrogen can be estimated straightforwardly while situation with energetic secondary neutral atoms is more complicated.

2.2 Interstellar helium atom flux

Space probe moves with the velocity **70 km/s** (which corresponds to the energy of **25 eV/nucleon**) relative to interstellar gas. The expected flux of interstellar helium atoms is then

$$\mathbf{F_{He} = n_{He} V_0 = 7\ 10^{4}\ cm^{-2}\ s^{-1}}$$

and an average energy of individual atoms is **100 eV**. The flux is expected from the well defined direction (direction of the vector of relative - between space probe and interstellar gas - velocity) and it is confined within **10° x 10°** solid angle (typical thermal velocity of atoms is **6 km/s**).

The first attempt to detect directly interstellar helium atoms will be carried out by Ulysses mission (*Rosenbauer et al, 1983; 1984*).

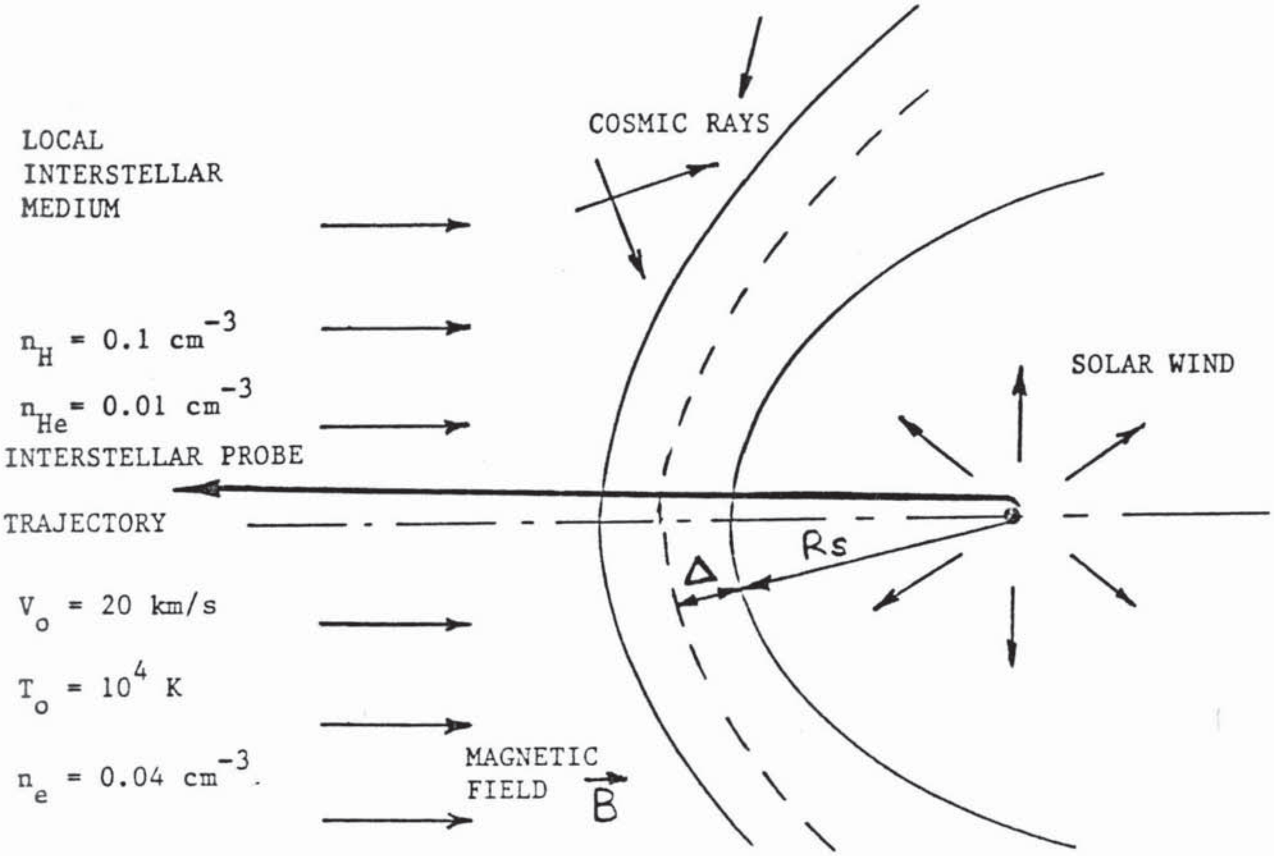

Fig.1. The INTERSTELLAR PROBE trajectory and plausible structure of heliosphere.

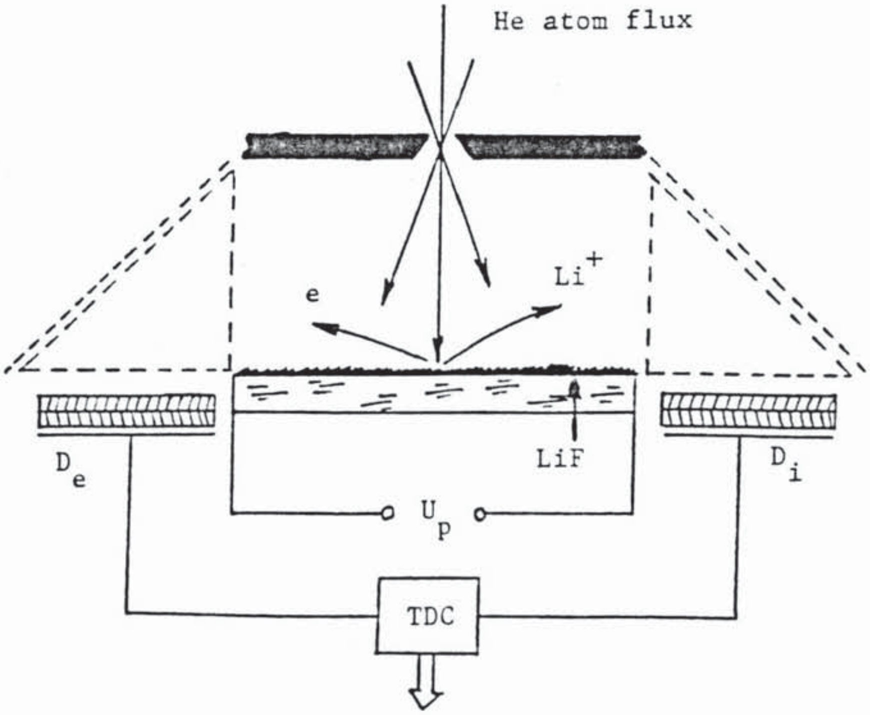

Fig.2. The interstellar helium atom flux detector NAD-1.
TDC - time-to-digital converter.

2.3 Heavier atom flux

One can expect also a flux of heavier interstellar atoms such as oxygen, nitrogen and neon which are present in local interstellar gas. Their number densities are $\mathbf{n_O = 10^{-4}\ cm^{-3}}$, $\mathbf{n_N = 2\ 10^{-5}\ cm^{-3}}$ and $\mathbf{n_{Ne} = 10^{-5}\ cm^{-3}}$ respectively (*Cummings and Stone, 1990*). Energy (as seen from the Interstellar Probe) of oxygen atoms is **400 eV**, nitrogen - **350 eV**, and for neon - **500 eV**. These fluxes are confined within the $\mathbf{5^\circ \times 5^\circ}$ solid angle and their expected intensities are

$$\mathbf{F_O = n_O\ V_0 = 7\ 10^{\,2}\ cm^{-2}\ s^{-1}}$$

$$\mathbf{F_{Ne} = n_{Ne}\ V_0 = 7\ 10^{\,1}\ cm^{-2}\ s^{-1}}$$

$$\mathbf{F_N = n_N\ V_0 = 1.5\ 10^{\,2}\ cm^{-2}\ s^{-1}.}$$

2.4 Interstellar hydrogen flux

Expected flux of interstellar hydrogen atoms is

$$\mathbf{F_H = n_H\ V_0 = 7\ 10^{\,5}\ cm^{-2}\ s^{-1}\ .}$$

An average energy of individual hydrogen atoms is **25 ev**, the flux is coming from the well defined direction and it is confined within $\mathbf{20^\circ \times 20^\circ}$ solid angle (typical thermal velocity of atoms is **12 km/s**).

2.5 Flux of energetic neutral atoms

The solar wind is a highly supersonic plasma flow into the local interstellar medium (LISM) which is characterized by a certain finite pressure (magnetic field + cosmic rays + thermal motion of atoms, ions and electrons) (fig.1). Therefore, this supersonic plasma flow has to stop and its kinetic energy has to be converted into the energy of thermal motion of plasma ions and electrons. Details of the interaction depend essentially on the assumed parameters of the LISM. What is important is that there has to be a very hot plasma at this region. Neutral interstellar gas atoms penetrate relatively freely through the interface region and there is a certain probability for "hot", energetic (> **100 eV**) ions to charge exchange with interstellar gas atoms and give rise to the ENAs. The velocities of these particles would reflect velocity distribution of ions and some of them would be directed back towards the Sun.

The solar wind consists mostly of protons (95 %) and doubly charged helium ions (5 %) with traces of the ions of other elements. These abundances and those expected in interstellar gas as well as the relevant charge exchange cross sections determine that the ENA flux from the heliospheric interface is that of **energetic hydrogen atoms**. Another pool of highly energetic ions, which may produce ENAs in a similar way (though charge exchange cross sections are lower) are anomalous cosmic rays (ACRs) which are born/accelerated somewhere in interface region and solar wind. There is no now adequate understanding of the origin of ACRs and the detection of ENAs from the interface may reveal some physical processes relevant to the genesis of ACRs.

Attempts to make estimates of the expected characteristics of the ENA flux from the interface are not numerous (e.g. *Bleszynski, 1987*). Obviously such analysis would depend substantially on the details of the interaction scenario. However, the expected flux can be easily estimated qualitatively from the following considerations.

Let the solar wind plasma termination shock be situated at a distance $\mathbf{R_S}$ from the Sun (fig.1). Solar wind plasma proton number density just before the shock transition is $\mathbf{N_{SW} = N_0 (R_0/R)^2}$, where $\mathbf{N_0}$ is the number density of solar wind protons at the Earth's orbit $\mathbf{(R_0 = 1\ AU)}$. According to Rankine-Hugoniot relations for a strong shock, the number density of protons after the shock is $\mathbf{N_P = 4\ N_{SW}}$. Let us assume also that the thickness $\mathbf{\Delta}$ of the layer containing hot solar wind plasma after the shock is much smaller than $\mathbf{R_S}$ and that the thermal velocities of the ions are much greater than the plasma bulk velocity. The ENA flux number density $\mathbf{(cm^{-2}\ s^{-1}\ sr^{-1})}$ for the observer "looking" at normal to solar wind termination shock ("optically thin" approximation) is then

$$\mathbf{F_{ENA} = N_P\, V_P\, \sigma\, \Delta\, n_H\, P\ /\ 4\,\pi}$$

where $\mathbf{V_P}$ is the "effective" speed of hot protons in the interface region, $\boldsymbol{\sigma}$ is the charge exchange cross section for protons on hydrogen atoms (which weakly depends on velocity), and $\mathbf{P}$ is the probability of an ENA to reach the observation point. It can be readily shown that $\mathbf{P}$ is close to unity everywhere except the region within several AU from the Sun.

We assume further that $\mathbf{V_P = 2\ 10^7\ cm/s}$ (and hence corresponding energy of ENAs is **200 eV**), $\boldsymbol{\sigma} \mathbf{= 3\ 10^{-15}\ cm^2}$, and $\mathbf{N_0 = 5\ cm^{-3}}$. Then

$$\mathbf{F_{ENA} = 1.5\ 10^5\ (\ R_0\ /\ R_S\ )^2\ (\ \Delta\ /\ 1\ AU\ )\ P} \qquad (\ 2\ )$$

where $\mathbf{\Delta}$ is in **AU**. If we assume that $\mathbf{R_S = 100\ AU}$ and $\mathbf{\Delta = 20\ AU}$, then the ENA flux would be about $\mathbf{F_{ENA} = 3\ 10^2\ cm^{-2}\ s^{-1}\ sr^{-1}}$. One can easily see that the high energy tail of the proton distribution would contribute more to the flux **F** due to larger values of **P** and higher velocities V_P, since $\sigma(V_P)$ decreases slowly with the increase of V_P. This fact is favorable since the efficiency with which ENAs can be detected increases rapidly with the increase of ENA energy. The flux F_{ENA} is proportional to the thickness, Δ, of the hot solar wind plasma and is inversely proportional to the square of the distance of this layer from the Sun. ENA emitting region is "optically thin" and this means that the expected flux would be higher for an oblique (with respect to termination shock) directions of observation. Therefore the measurement of ENA flux distribution over the sky by the Interstellar Probe opens the opportunity to determine in advance (before crossing the shock, while the probe approaches it) position of the termination shock. Extensive simulation of the expected ENA flux is certainly needed for accurate estimates of its characteristics. However, the qualitative dependence obtained here is a good indication that some major characteristics of the interface region as well as location of the termination shock can be derived from measurements of the ENA fluxes by the Interstellar Probe remotely.

The time needed for an energetic hydrogen atom to reach an observation point depends on the place of origin of the atom and its velocity. For instance, for **200 eV** hydrogen ENA, it would take more than two years to cross the distance of **100 AU**. Therefore, the measurement of velocity (energy) distribution of ENA atoms would give also the possibility to study temporal evolution of the processes in the interface region.

The first attempt to detect directly ENAs from heliospheric interface will be carried out by Relikt-2 mission (*Gruntman and Leonas, 1986; Gruntman et al, 1990*).

2.6 Hostile background and experimental approach

The expected neutral atom number density is very low - 10^{-5} - 10^{-1} cm^{-3} - therefore any conventional experimental technique (based on ionization of the neutral atom and subsequent analysis and detection of the ion) is not applicable. However, the energy of atoms may be sufficient to produce secondary emissions while bombarding sensitive/conversion surfaces. Interplanetary space is characterized by a high level of the background radiation of FUV/EUV photons, which also produce photoemission with rather high efficiency. The majority of background photons are hydrogen Lyman-alpha (1216 Å) with flux equal to **300-600 R** (**1 R = 1 Rayleigh** = $10^6 / 4\pi$ phot cm^{-2} s^{-1} sr^{-1}) and He resonance line (584 Å) with flux **1-10 R** at the Earth's orbit. Intensity of the background radiation would decrease gradually with the increase of the distance of the Interstellar probe from the Sun. Anyway the photon flux is much higher than the expected flux of neutral atoms.

Experimental conditions really present a challenge and can be summarized as following:

1. Fluxes of interstellar helium and hydrogen atoms are not omnidirectional but are are confined within a relatively large solid angle whereas fluxes of ENAs and background photons are of a diffuse type;
2. The neutral atom fluxes are much smaller than that of photons and as a concequence the expected count rates of detectors (based on secondary electron emission) due to background photons would be much greater than those due to atoms;
3. The absolute values of the neutral atom fluxes are very low, however long exposures (days and even weeks) to accumulate a signal are possible.

The only feasible experimental approaches to cope with the above conditions are: i) to arrange the instrument in such a way that neutral atoms interact with sensitive/conversion surface in a way absolutely different from that of photons, or ii) to use a coincidence technique. The former approach is implemented in the interstellar hydrogen detector (NAD-2), the latter one - in the ENA detector (NAD-3), and both together are utilized in the interstellar helium detector (NAD-1).

As far as the coincidence technique is concerned, the instrument has to be designed in such a way that arrival of an ENA may result in two separate, detectable phenomena and an arrival of photon can result in only one phenomenon. Then only the detection of these two separate phenomena "simultaneously", i.e. coincidence, would correspond to the registration of the ENA, and "noise coincidences" would be due to accidental arrival of the photons within the coincidence time gate. Such an approach gives an opportunity to extract a weak signal from highly superior photon background, although a low detection efficiency for coincidences may require rather long exposures. However, coincidences alone can not solve the problem since interplanetary space is filled also with high energy **(> 100 keV)** charged particles - solar and non-solar cosmic rays - with the flux even at quiet conditions as high as **1 cm^{-2} s^{-1} sr^{-1}** at the Earth's orbit. It is assumed here that simple deflection system - either electrostatic or based on permanent magnets - is installed at the entrance to prevent ambient plasma ions and electrons from enetering the instruments. However cosmic ray particles have an energy too high to be prevented from entering the instrument by the deflection system and hence they would produce coincidences with a very high efficiency - close to unity. Therefore, identification of the incoming particles (measurement of the velocity or energy) is needed.

III. NEUTRAL ATOM DETECTOR NAD-1

The proposed NAD-1 is a modification of the detector for the direct *in situ* study of neutral helium atoms penetrating solar system (*Rosenbauer et al, 1983, 1984*) for Ulysses (earlier ISPM) mission. In the original design the key element of the instrument is a **LiF** sensitive/conversion surface. This surface is bombarded by interstellar helium atoms as well as background photons. Emitted secondary particles - secondary electrons and ions (mostly **Li^+**) - are measured alternatively (two modes of measurement). **LiF** is known to be higly transparent to Lyman-alpha photons (and consequently to have low photoemission coefficient) which dominate in the background radiation. Therefore at favorable conditions the count rate of secondary electrons may be determined mostly by the neutral atom flux. On the other hand, photons can not sputter secondary ions (or to say more accurately, photons would produce secondary ions with extremely low efficiency through inelastic processes). Therefore the count rate of secondary ions would be almost totally due to the neutral atom flux. In that case the noise count rate of the detectors is due to the stray photons and particles within the instrument, cosmic rays, radioactivity of the spacecraft, and inherent noise of the detectors. The noise count rate may be, in principle, directly measured (by scanning the sky in the directions from which no flux of interstellar helium atoms is expected) and taken into account to a certain extent. However, more reliable detection of helium atoms remains desirable.

The modification of the original instrument is based on the idea to register helium atoms in a coincidence mode detecting secondary electrons and secodary ions simultaneously emitted from the sensitive surface (*Gruntman and Morozov, 1983; Gruntman and Leonas,* *1983*). An essential additional element is a proposal by *Rosenbauer, 1984* to use a semiconducting sensitive surface. The technique implemented in the NAD-1 is a part of the recently developed new approach to the study of secondary ions by time-of-flight (TOF) technique (*Gruntman, 1985, 1989*). The idea is, while retaining as much as possible of the proved original design (baffle and charge particle deflection system, preparation and control of the quality of **LiF** sensitive surface, etc), to measure simultaneously both emitted secondary electrons and secondary ions. These two channels (counting secondary electrons and secondary ions) correspond separately (but functioning now at the same time) to two modes of operation of the original instrument design. However, in this case a new opportunity appears, namely to count also coincidences, i.e. simultaneous detections of secondary electrons and secondary ions. This approach was tested in the lab (for different sensitive surface) and proved to be successful (*Gruntman, 1989*).

The proposed NAD-1 principal scheme is shown in fig.2. Particles and photons hit a semiconducting plate (e.g. semiconducting glass used in the manufacturing of microchannel plates - MCPs) covered by thin layer of **LiF**. Voltage $\mathbf{U_P}$, applied across the semiconducting plate, creates an electric field along the sensitive surface which separates secondary electrons and secondary ions and accelerates them to opposite directions. After turns in corresponding electrostatic mirrors secondary particles are registered by detectors $\mathbf{D_e}$ and $\mathbf{D_i}$ (MCP detectors). The turns in electrostatic mirrors are necessary to protect detectors $\mathbf{D_e}$ and $\mathbf{D_i}$ from i) stray photons and particles (mostly electrons); ii) particles reflected from the sensitive surface as neutrals; iii) detector ion feedback. Such a scheme gives an opportunity to measure separately (and simultaneously) secondary electron and secondary ion count rates as well as coincidence count rate, i.e. count rate of the events when both secondary electron and secondary ion are emitted from the sensitive surface by the same incident particle. Moreover, the measurement of the time interval between detections of secondary electron and secondary ion would determine the exact position at which the particle impinged since this time interval depends only on the mass of the sputtered ion, which is known to be $\mathbf{Li^+}$, and the position of the impinge point at the sensitive surface.

The velocity distribution of helium atoms can be determined not by measurement of atom energies (velocities) but by registering the image of a mask installed in the flux of atoms (*Gruntman, 1980*). Installing a simplest mask - a rectangular slit - at the entrance of the detector and measuring a time-of-flight distribution, one would get the distribution of perpendicular (in one dimension) velocities of helium atoms. Helium atoms coming at different angles (i.e. with different velocities perpendicular to the slit) would hit different places at the sensitive sureface. The measurements of the times of flight of lithium ions would determine the position of the origin and consequently the angles of the incidence of incoming helium atoms.

The Interstellar Probe is spin stabilized. So, if the NAD-1 is oriented along the spin axis in antisolar direction, then two-dimensional perpendicular velocity distribution would be measured without implementing any mechanically moving parts and/or platform.

Let us assume that UV background flux (worst case - at Earth's orbit) is $F_\nu = 5\ 10^7\ cm^{-2}\ s^{-1}\ sr^{-1}$ and $F_{He} = 7\ 10^4\ cm^{-2}\ s^{-1}$. Then the count rate of the electron detector D_e would be $I_e = F_\nu\ (S_d\ \Omega_d)\ \epsilon_\nu$, where ϵ_ν is the efficiency for a UV photon to produce photoelectron and $(S_d\ \Omega_d)$ is the instrument throughput. We assume also that efficiencies to produce any secondary particle include also corresponding efficiencies to transport this particle to and to register by the appropriate detector. Let us assume that most of the counts of ion detector I_i are not due to secondary ions (which are a minority) but some kind of noise (stray photons within instrument mostly). We assume here that this noise is proportional to photon flux, i.e. $I_i = F_\nu\ (S_d\ \Omega_d)\ K_\nu$, where K_ν is the efficiency with which incoming photon would trigger ion detector. Then the coincidence count rate due to the neutral atom flux would be $I_{CO}^{He} = F_{He}\ (S_d\ \Omega_d)\ \epsilon_{He}$, where ϵ_{He} is the product of the probabilities to produce secondary electron and secondary ion at the point of impinge on the sensitive surface. The noise coincidence count rate due to simultaneous triggering of ion and electron detectors by photons is $I_{CO}^{NOISE} = I_i\ I_e\ \tau_0$, where τ_0 is the width of the time gate for coincidences.

The ratio of absolute values of signal to noise is then

$$\rho = I_{CO}^{He} / I_{CO}^{NOISE} = (F_{He} / F_\nu)\ \epsilon_{He} / (F_\nu\ (S_d\ \Omega_d)\ K_\nu\ \epsilon_\nu\ \tau_0)$$

The ratio (F_{He} / F_ν) is almost constant within the solid angle where helium flux is confined and signal to noise ratio is inversely proportional to instrument throughput $(S_d\ \Omega_d)$

and can be increased by decreasing, for instance, aperture. However, this will result in an undesirable effect - a decrease of the absolute value of the signal, which is rather low. Any instrument of the kind under present discussion has inherent ability, as was shown by *Gruntman and Leonas, 1986; Gruntman et al, 1990,* to monitor the "noise" coincidence rate by counting coincidences of detectors' counts which are not connected causally, for instance in this case, when a "secondary ion" is detected earlier than a "secondary electron." Hence, "pure noise (random) coincidences" can be subtracted later and the signal to noise ratio would be further improved.

Another attractive feature of the presented coincidence technique is an opportunity to determine, as it was shown by *Gruntman and Morozov, 1982*, absolute atom flux without *a priori* knowledge of yields and detection efficiencies of secondary electrons and ions in the absence of noise counts (or when their rates are known). This is also the way to receive important instrument housekeeping information.

In the presently proposed scheme detector count rates must be lower than $\mathbf{I_{MAX} = 10^4\ s^{-1}}$ and consequently the instrument throughput must not exceed

$$(\mathbf{S_d\ \Omega_d}) = \mathbf{I_{MAX}} / (\mathbf{F_\nu}\ \epsilon_\nu)$$

If we asume $\epsilon_\nu = \mathbf{10^{-2}}$, then $(\mathbf{S_d\ \Omega_d}) = \mathbf{2\ 10^{-2}\ cm^2\ sr}$. It is reasonable to select a field of view $\mathbf{\Omega_d = 20° \times 20°}$ to accomodate all helium flux (with the wings) and a sensitive area as a rectangular slit $\mathbf{S_d = 0.1 \times 1 = 0.1\ cm^2}$. If we assume also that the noise count rate of the ion detector is $\mathbf{I_i = 10\ s^{-1}}$, coincidence time gate $\tau_0 = \mathbf{1\ \mu s}$, then the absolute noise, i.e. random coincidence count rate, would be $\mathbf{I_{CO}^{NOISE} = 10^{-1}\ s^{-1}}$. The probability to produce simultaneously secondary electron and secondary ion by helium atom with the energy of **100 eV** were not measured. However, from independent measurements of ion and electron emmisions separately (*Rosenbauer et al, 1983; 1984*), one can assume (conservative estimate) that the probability of simultaneous emission is equal to $\epsilon_{\mathbf{He}} = \mathbf{10^{-4}}$. Then the signal count rate would be slightly larger than the noise coincidence rate, i.e. $\mathbf{I_{CO}^{He} = 1.5\ 10^{-1}\ s^{-1}}$. Such a level of count rate corresponds to more than **10^4 count/day**. The accumulation time of several days or a week is readily feasible and subtraction of noise coincidences would improve dramatically final signal to noise ratio. It should also be noted that UV background radiation intensity diminishes with the increase of the distance from the Sun. For instance, the photon flux in Lyman-alpha is approximately only **50 R** at the distance of **25 AU** from the Sun and diminishes further approximately inversely proportional to the distance from the Sun (e.g. *Gangopadhyay et al, 1989*). The random coincidences are proportional to the square of the photon intensity and would diminish very rapidly as the Interstellar Probe moves from the Sun.

In this way, the NAD-1 will be able to measure the perpendicular velocity distribution function of interstellar helium atoms. The space probe spinning would provide an opportunity to determine the off-set angle between the probe's trajectory and interstellar gas velocity direction. Fluxes of heavier interstellar atoms will also be registered by the NAD-1. Detection efficiencies for such atoms would be much greater and those atoms are concentrated in a narrower solid angle. However, it is difficult to assess now the possibility to measure fluxes of heavier atoms and further laboratory experiments are necessary to explore this opportunity.

IV. NEUTRAL ATOM DETECTOR NAD-2

The detection of interstellar hydrogen is more difficult: energy of the hydrogen atoms - **25 eV** - is not enough to produce simultaneous emissions of a secondary ion and a secondary electron with acceptable efficiencies. However, there exists a technique which is well developed for the laboratory applications, i.e. the production of high intensity negative hydrogen/deuterium ion beams which after stripping are used for fusion plasma energy pumping. The use of this technique for direct detection of interstellar hydrogen atoms was first proposed by *Gruntman and Leonas, 1983* .

Neutral hydrogen atoms after collision/reflection with certain types of surfaces acquire with relatively high efficiency a negative charge, i.e. become negative ions. The efficiency of such a conversion depends on the atoms initial velocity, angle of incidence, and the type of surface with which it interacts. The most developed and well studied conversion surfaces are metals covered by alkali layers, e.g. by cesium. The negative hydrogen ion yield is a convolution of the reflection coefficient and the charge transfer probability. The charge transfer probability depends on both components of the atoms velocity, parallel and perpendicular to the surface. Typical velocity of interstellar hydrogen atoms is much smaller than electron velocities in cesiated surfaces, therefore the charge transfer probability is determined mostly by the atoms velocity component normal to the surface (*Van Wunnik et al, 1983a*). Let us assume that interstellar hydrogen atoms normal velocity is **50 km/s**, which corresponds to **45°** angle of incidence on conversion surface. Then the fraction of negative ions in the particles reflected from the tungsten surface (100) covered by a thick layer of cesium, is **10 %** . A very thin cesium layer (half a monolayer) may give negative ion fraction as high as **40 %** (*Van Wunnik et al, 1983a*), however, from a practical point of view, to maintain such a surface in a space instrument may be too difficult and the use of thick cesium layer seems to be preferable. Overall conversion coefficient of several per cent (*Schneider et al, 1981; Van Wunnik et al, 1983b*) could be expected for interstellar hydrogen atoms. Metal surfaces covered by layers of another alkalis such as **Rb** or **K** can also be used for conversion of hydrogen atoms (*Schneider et al, 1981*).

Certainly the stability of the surfaces and the necessity to refresh them during long space flight requires further study. However, one may safely assume as a conservative estimate the value of $\epsilon_{H^-} = 0.01$ for such conversion coefficient for interstellar hydrogen atoms. Negative hydrogen ions which originate after interaction with a conversion surface are unique and can be "assuredly" detected with essentially negligible noise by a coincidence technique.

A possible version of the NAD-2 instrument is shown in fig.3. Interstellar hydrogen atoms hit the cesiated surface and are converted partially to negative ions. Background UV photons as well as atoms also produce secondary electrons with high efficiency. As it has been mentioned, the UV background would decrease with the Interstellar Probe moving away from the Sun. Negatively charged particles (ions and electrons) are accelerated up to a fixed energy (say, 5-6- keV) and are separated from electrons according to their masses in a simple magnetic analyzer. Then negative ions enter a simple TOF section. They penetrate a thin (**100 Å**) foil and reach (and are registered by) detector **D** . Secondary electrons are emitted from the foil due to penetration by the particle. Electrons are accelerated by an electric field after the foil, overrun heavier hydrogen atoms and reach first the detector **D** . So hydrogen ions are detected in the coincidence mode with all its inherent

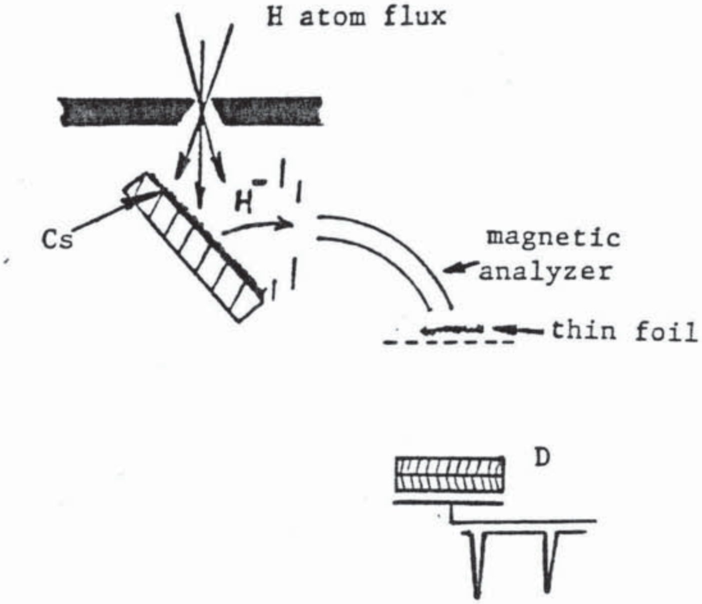

Fig.3. The interstellar hydrogen atom flux detector NAD-2.

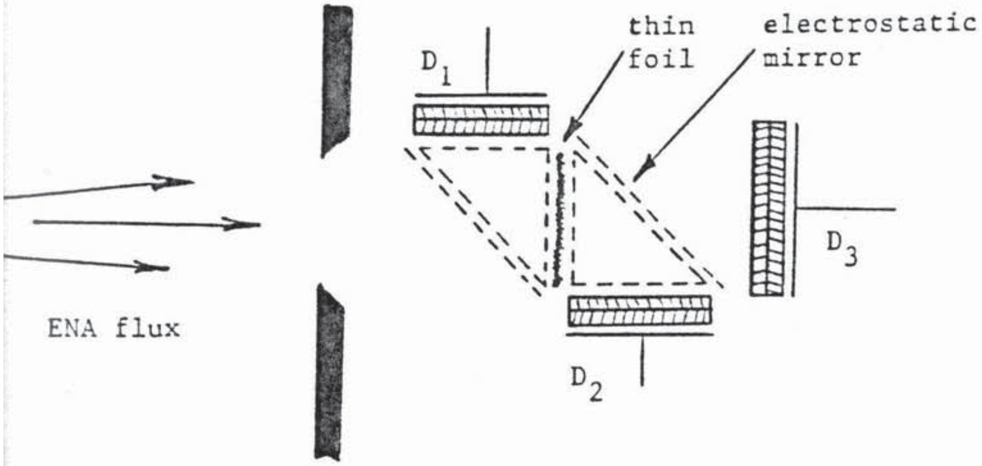

Fig.4. The energetic neutral atom flux detector NAD-3.

"benefits", as it has been already discussed, i.e. virtually zero noise, determination of the absolute value of the ion flux as well as detector efficiency, etc. By measuring the time interval between two pulses from the detector one could determine the velocities of the registered particles. This TOF scheme (one channel TOF) is very simple and has a rather high overall detction efficiency of 20 - 40 % (*Gruntman and Morozov, 1982*). However, for the sake of redundancy, a conventional two channel TOF scheme may be implemented. TOF and coincidence technique, as well as selection of particles in an magnetic analyzer result in essentially noise-free "assured" detection of negative hydrogen ions.

The total detection efficiency of the instrument would be **10^{-3}** with almost complete noise suppression. If the detector of electrons and atoms **D** is a one-dimensional (in the direction perpendicular to the plane of the figure 3) position-sensitive one (say, MCP stack with simple collector composed of **12-16** strips - collector elements), then the NAD-2 with a slit at the entrance may determine the temperature of the interstellar hydrogen atom flux in the same way as the NAD-1. Another opportunities are i) to perform an energy analysis of negative hydrogen ions, as was discussed by *Massmann et al, 1979*; and ii) to the use the dependence of the conversion efficiency on the angle of incidence (e.g. by tilting conversion surface) of the atoms. For the same instrument throughput as that of the NAD-1, the signal count rate of the NAD-2 would be not less than **$10\ s^{-1}$**, which corresponds to almost a million counts for one day of measurements.

The NAD-2 instrument may also be used for registration of ENAs from heliospheric interface region. These particles could be separated from interstellar gas hydrogen atoms by the proper choice of accelerating voltage for negative ions before entrance to magnetic analyzer.

V. NEUTRAL ATOM DETECTOR NAD-3

The proposed instrument NAD-3 is essentially the same in ideology as the one under preparation for the **Relikt-2** mission (*Gruntman and Leonas, 1986; Gruntman et al, 1990)*, but optimized for the particular problem to measure ENAs from the heliospheric interface. The modification of the original design concerns mostly a proper choice of the dimensions of the sensitive area, the distances between the sensitive element and the detectors, solid angle, flight length, etc.

The principal scheme of the proposed instrument is shown in fig.4. Background photons and ENAs bombard a thin (**40-60 Å**) carbon foil. Incoming photons are either absorbed by the foil (with possible emission of photoelectrons) or fly through it to the detector $\mathbf{D_3}$. Electrons, emitted from the foil (forward and backward), are accelerated, and after deflection by electrostatic mirrors are directed to detectors $\mathbf{D_1}$ and $\mathbf{D_2}$ respectively. The incoming ENAs suffer some energy loss (which may result in emission of electrons) while penetrating the foil and proceed to the detector $\mathbf{D_3}$ with reduced energy and a somewhat changed trajectory due to scattering. An arrival of a photon in the instrument can result in triggering of either $\mathbf{D_3}$ or $\mathbf{D_1(D_2)}$ and an arrival of an ENA may result in triggering of $\mathbf{D_3}$ and $\mathbf{D_1}$ (and/or $\mathbf{D_2}$), i.e. in coincidence. Noise background coincidences may be caused only by arrival (and registration) of two photons simultaneously. Measurement of the time interval between the detection of an electron and detection of a neutral atom by $\mathbf{D_3}$ gives the possibility to determine the velocity of ENA. The latter ability is very important since it gives an effective way to discriminate against cosmic ray particles. The velocities of cosmic ray particles (and time of flight) would be clearly distinct from those of ENAs, and cosmic rays will therefore be neglected further in our analysis. The width of the coincidence time gate and hence the noise coincidence count rate are proportional to the maximum possible time of flight of the neutral atom between the foil and detector $\mathbf{D_3}$. To minimize the noise, this flight distance has to be as small as possible. The sensitive area of the detector $\mathbf{D_3}$ should be larger than that of the thin foil in order to also collect neutrals which scatter substantially during penetration of the foil.

Several types of coincidences and TOF spectra are to be measured:

i) The coincidence count rate from electron detectors $\mathbf{D_1}$ and $\mathbf{D_2}$ (coincidence time gate for such coincidences may be very short, $\boldsymbol{\tau_e = 2}$ **ns**);

ii) Three TOF spectra (and three different coincidence count rates respectively); the **STOP** signal is provided by detector $\mathbf{D_3}$ and there are three diffrent ways to produce the **START** signal: a) $\mathbf{D_1}$ is triggered and $\mathbf{D_2}$ is not triggered, i.e. $\mathbf{(D_1)AND(NOT(D_2))}$; b) $\mathbf{(NOT(D_1))AND(D_2)}$; c) $\mathbf{(D_1)AND(D_2)}$, i.e. tripple coincidence.

The absolute values of the detectors' count rates are determined by the background photon flux and we assume the maximum possible count rate for any detector $\mathbf{I_{MAX} = 10^4}$ $\mathbf{s^{-1}}$. We assume also that the probability for a photon to produce a photoelectron, which is transported to detector $\mathbf{D_1}$ or $\mathbf{D_2}$ and registered is the same as the probability to penetrate the foil and trigger detector $\mathbf{D_3}$ and is equal to **0.01**, i.e. response of each detector for incident photon flux is $\boldsymbol{\epsilon_\nu = 0.01}$. The maximum possible value of the instrument throughput is then $\mathbf{(S_d\ \Omega_d) = 2\ 10^{-2}\ cm^2\ sr}$ (say, for an instrument with thin foil sensitive area $\mathbf{S_d = 0.5\ cm^{-2}}$ and an instrument field of view solid angle $\mathbf{\Omega_d = 10^\circ \times 10^\circ}$). For a realistic distance between the foil and $\mathbf{D_3}$ of **1 cm** and for the energy (minimum) of a still detectable hydrogen ENA (after the foil) of **100 eV** (velocity $\mathbf{1.4\ 10^7\ cm/s}$), the time of flight would be **70 ns**. The maximum expected energy of ENAs from the interface, corresponding to high speed wing of proton distribution in plasma, can be assumed to be close to **1400 eV** with the corresponding time of flight **20 ns**, then the coincidence time gate would be $\boldsymbol{\tau_0 = 50}$ **ns** . The noise coincidence count rate ($\mathbf{D_1}$ or $\mathbf{D_2}$, and $\mathbf{D_3}$) for the worst case (at **1 AU** from the Sun) would be

$$I_{CO}^{NOISE} = (\ F_\nu\ (S_d\ \Omega_d)\ \epsilon_\nu\ )^2\ \tau_0 = 5\ s^{-1}$$

As it has been noted, the UV background depends on the distance from the Sun. The noise coincidence count rate would quickly diminish as the Interstellar Probe moves away from the Sun. The detection efficiency for double coincidences is $\boldsymbol{\epsilon_{ENA} \leq 0.01}$ (*Gruntman and Morozov, 1982*), and the expected signal due to ENAs would be

$$I_{CO}^{ENA} = F_{ENA}\ (S_d\ \Omega_d)\ \epsilon_{ENA} = 6\ 10^{-2}\ s^{-1}$$

During a **10** day exposure, there would be accumulated $\mathbf{\approx 4\ 10^{6}}$ noise coincidences and $\mathbf{\approx 5\ 10^4}$ coincidences due to ENAs. As it has already been mentioned for the NAD-1, the NAD-3 also has the inherent ability to monitor the "noise" coincidence rate by counting coincidences of detectors' counts which are not connected causally. In this particular case, this means the event when a neutral atom is detected by $\mathbf{D_3}$ earlier than the corresponding secondary electron from the foil by $\mathbf{D_1}$ or $\mathbf{D_2}$. Hence, "pure noise coincidences" can be subtracted later improving the signal to noise ratio. For a 10 day exposure, the expected noise level can be determined with an accuracy better than $\mathbf{10^4}$ counts **(3σ)**, and consequently the ENA flux could be reliably measured.

Double coincidence of electron detectors ($\mathbf{D_1}$ and $\mathbf{D_2}$) would give a random coincidence count rate of **$0.2\ s^{-1}$**, which is much larger than coincidences due to ENAs (**$6\ 10^{-2}\ s^{-1}$**, if the same detection efficiency **$\epsilon_{ENA} = 0.01$** is assumed). It should be noted that cosmic ray particles would produce also such coincidences with very high efficiency.

However, the tripple coincidences may give an opportunity to measure the ENA flux directly (without subtracting the noise count rate). If we assume that the detection efficiency for ENAs (tripple coincidences) is **$\epsilon_{ENA} = 1.5\ 10^{-4}$**, then the expected count rate would be **$10^{-3}\ s^{-1}$** (i.e. **100** counts a day). However, for photons, the tripple coincidence count rate would be only

$$I_{CCC} = (\ F_{\nu}\ (S_d\ \Omega_d)\ \epsilon_{\nu}\ )^3\ \tau_0\ \tau_e = 10^{-4}\ s^{-1}$$

So, the absolute value of the signal would be much higher than for the noise coincidences.

It is important to mention here that background photons more energetic than hydrogen Lyman-alpha (the most important line is **584 Å**) may produce simultaneous emission of two photoelectrons from different sides of the thin foil and create a **(D_1)AND(D_2) START** signal and possibly tripple coincidence if another photon triggers **D_3** simultaneously. The efficiency of such double photoelectron emissions is poorly known. However, if this efficiency is less than **$2\ 10^{-3}$**, which is probably the case, then tripple coincidences due to the helium resonance line at **584 Å** (which is approximately **100** times weaker than Lyman-alpha) would be less numerous than random tripple coincidences due to background photons.

There exists also an untested opportunity to introduce an additional coincidence channel by using in detector **D_3** the input MCP with an ion barrier film. It would diminish to a certain extent the detection efficiency of **D_3**, but secondary electrons that would be emitted (backward) when an ENA is registered, can be sent to an additional detector (vis-a-vis to **D_2**) and registered.

VI. CONCLUSION

Direct experimental study of interstellar neutral atoms by the Intestellar Probe Mission is a difficult task but it is far from being hopeless. As the discussion in this work shows, almost all necessary experimental techniques have either already been space flight tested, or will have been flight proved within a few year time, or have been proved at the laboratory.

What is necessary to do now is to put all of them together and build laboratory prototypes of the instruments. Their extensive testing as well as the study of the characteristics of key components (MCP life time, Cs and LiF surface control and stability, emission coefficients and yields, etc) and the possible rocket and Shuttle flights of the instruments will provide the basis for the final design of the flight instruments for the Interstellar Space Probe.

Direct measurement of interstellar gas as well as ENAs from the heliospheric interface region will be an important contribution to the success of this exciting mission to the "last frontier" of our Solar System.

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