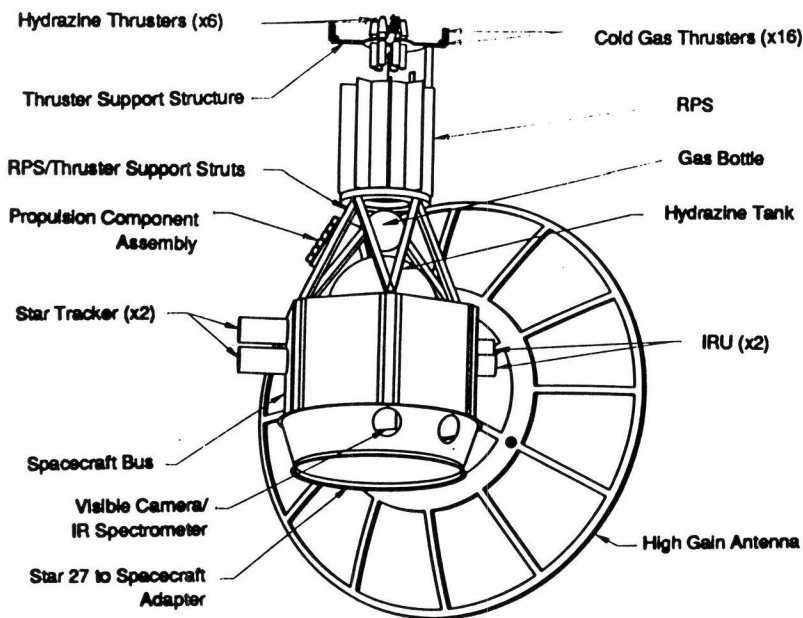


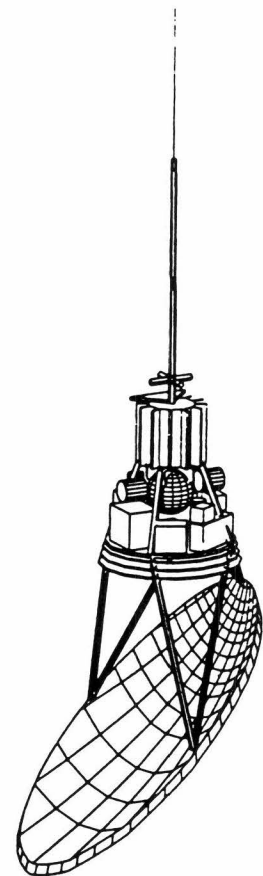
SMALL INSTRUMENTS FOR SPACE PHYSICS

PROCEEDINGS OF THE SMALL INSTRUMENT WORKSHOP HELD IN
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The baseline PFF spacecraft



The Small Solar Probe

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IN SITU MEASUREMENT OF NEUTRAL PARTICLES DURING THE INTERSTELLAR PROBE MISSION

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ABSTRACT

Interstellar Probe mission is a unique opportunity to measure characteristics of the local interstellar medium and heliospheric boundary. The study of the interstellar gas (ISG), including its composition and the degree of ionization, would be in the focus of such a mission. Heliospheric boundary, the region between the solar wind termination shock and the heliopause, contains hot plasma of the solar wind and is the source of the heliospheric energetic neutral atoms (HELENA's). Measurement of the energy distribution and intensity of the HELENA's should provide information about the shape of the heliosphere and physical process at this solar system frontier. Two instruments are proposed for the study of the neutral atoms on the Interstellar Probe. Interstellar hydrogen, deuterium, and oxygen atoms can be measured *in situ* by using a novel technique based on conversion of neutral particles into negative ions on specially prepared surfaces. A novel concept of the simple compact instrument to detect HELENA's is presented. The latter instrument ideally fits the conditions of measurements performed at large distances from the Sun.

I. Introduction

The study of neutral atoms was not historically at the top of the agenda in space physics where interest has been traditionally concentrated on plasma, energetic particles and fields. Partially this can be explained by seemingly unsurmountable experimental difficulties to measure dilute (10^{-6} - 10^{-1} cm^{-3}) populations of neutral atoms. This perception is changing slowly and neutrals are gaining recognition as a unique and efficient tool for the study of many phenomena in the heliosphere. The development of new experimental techniques has aided in this process. It is sometimes overlooked that 98-99% of the mass of matter filling the heliosphere, if one excludes the sun, planets, and other celestial bodies, is represented by the neutral particles and the remaining 1-2 % only is the solar wind plasma. Planned Interstellar Probe mission presents a unique opportunity to study various populations of neutral atoms.

A study of the interstellar gas (ISG) from the local interstellar medium (LISM) is a vast source of information on the properties of the LISM. Measurement of the composition of the ISG may provide critical evidence for Big Bang cosmology, the theory of the stellar formation and evolution, and origin of anomalous cosmic rays. A discussion of what can be learned by direct, *in situ* measurement of the ISG composition is given by *Gruntman, 1993b*. An expanding supersonic flow of the solar wind interacts with the LISM forming the heliosphere (fig.1). Experimental data on the morphology of the heliospheric boundary are scarce and indirect.

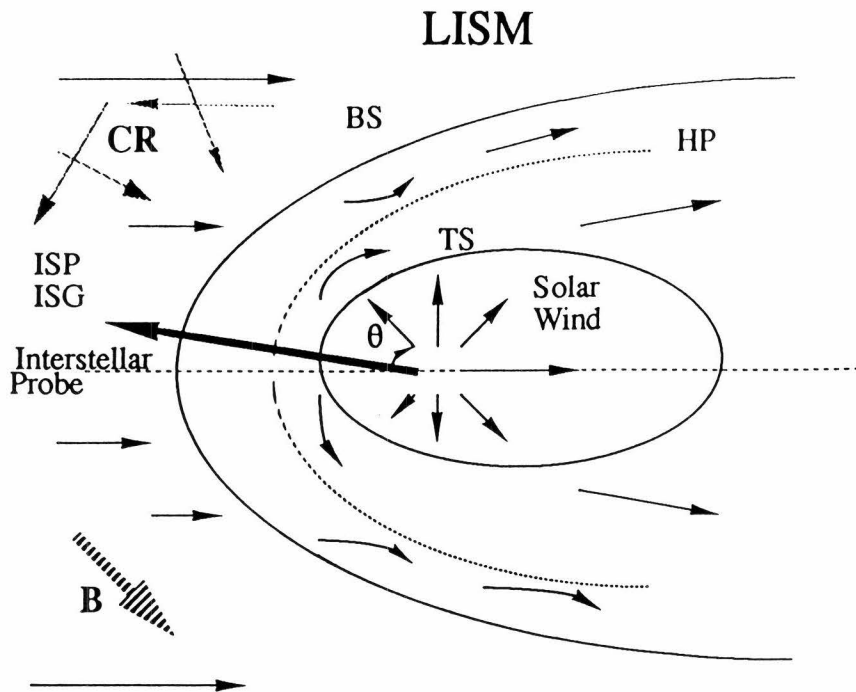


Fig.1. Two-shock model of the interaction of the solar wind with the local interstellar medium. LISM - local interstellar medium; TS - termination shock; HP - heliopause; BS - bow shock; CR - cosmic rays; ISP (G) - interstellar plasma (gas); B - magnetic field. The Interstellar Probe trajectory is in upwind direction.

Heliospheric boundary, the region between the solar wind termination shock and the heliopause, contains hot plasma of the solar wind origin and is the source of the heliospheric energetic neutral atoms (HELENA's). Characteristics of the low-energy HELENA flux are highly sensitive to the process at the heliospheric boundary [Gruntman, 1992] and measurement of the energy distribution and intensity of the HELENA's would provide information about the shape of the heliosphere and physical process at this solar system frontier.

2. Measurement of the composition of the ISG

The expected composition of the ISG is briefly discussed in the accompanying paper by Gruntman, 1993a. The velocity, V_{SC} , of the Interstellar Probe spacecraft will be about 50 km/s (10 AU/year) and the ISG velocity relative to the spacecraft, $V_{ISG} + V_{SC}$, will be about 75 km/s. The interstellar atoms would come into the instrument from slightly different directions due to ion thermal velocities. Figure 2 shows the angular dependence of the atom fluxes for

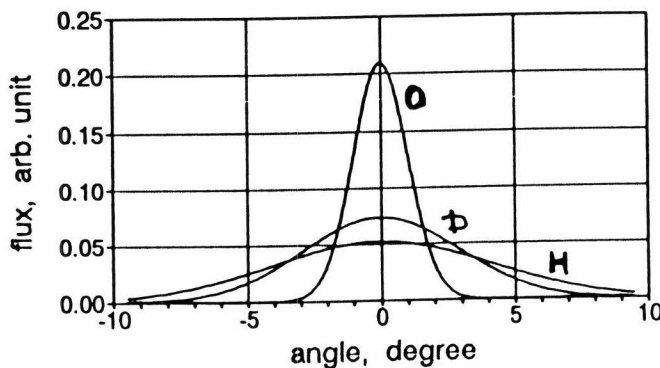


Fig.2. Angular dependence of the interstellar atom flux for H, D, and O. The ISG temperature is 7000 K; the velocity relative to the spacecraft is 75 km/s.

different ion species. One can see that practically all flux of oxygen atoms is confined within the 5° angle while hydrogen atoms are confined within the angle of about 15°. These dependencies determine requirements to the instrument field-of-view.

For a realistic number density of hydrogen atoms in the LISM, $n_H = 0.1 \text{ cm}^{-3}$, one can expect that atom number densities of deuterium and oxygen would be 10^{-6} and 10^{-4} cm^{-3} correspondingly. The suggested experimental approach is based on the particle conversion on the surface into negative ions and subsequent analysis and detection of these ions. It is important that negative ions are not present in the ambient solar wind plasma in interplanetary space and interstellar plasma and that they are born only as a result of the interaction of the incoming neutral particle flux with a specially prepared conversion surface. Such a conversion technique was suggested for use in space instrumentation and analyzed in detail by *Gruntman, 1993b* (see also references therein). The general scheme for the detection and analysis of neutral particle fluxes is presented in Figure 3. Charged particles, ions and electrons are prevented from entering the instrument by either an electrostatic or magnetic deflection system (not shown). Incoming neutral particles (N) hit the conversion surface (CS) and are converted to negative ions. The negative ions are accelerated and momentum-selected in the magnetic analyzer before entering the time-of-flight (TOF) analyzer for final detection. The TOF section provides an assured, essentially noise-free detection (double and/or triple coincidences) and additional identification of the mass-selected negative ions, and hence incoming neutral atoms. The latter feature is of great importance for the ISG study, because fluxes of such minor ISG constituents as oxygen and especially deuterium are extremely low, and "assured" detection is crucial for long accumulation times. The magnetic analyzer can be built on the basis of permanent magnets and scanning across the mass range is performed by changing the energy of negative ions.

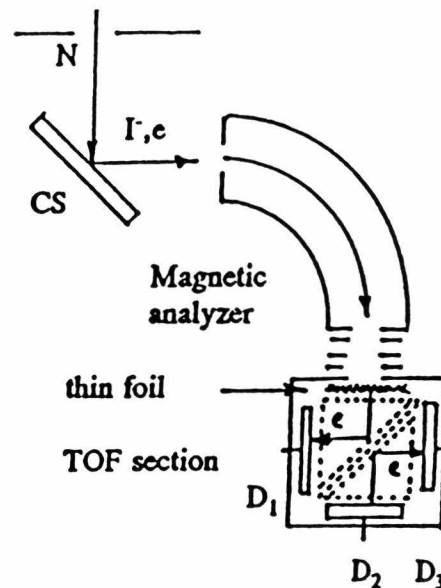


Fig.3. General scheme for detection and analysis of neutral atom fluxes. N - neutral atom; Γ - negative ion; CS - conversion surface; D_1 , D_2 , D_3 - microchannel plate detectors.

The efficiency of atom conversion depends on the type of atom, the atom's 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 cesium, which provide the highest values of conversion efficiency which may be as large as 10 % for atom velocities typical for the ISG. Other surfaces are being currently studied as converters (see discussion by *Gruntman, 1993b* and references therein) and some of them show promising characteristics, in particular complex multi-component cesium oxide mixture, $\text{Cs}/\text{Cs}_2\text{O}/\text{Cs}_2\text{O}_2$, as well as LaB_6 and Ba .

For the detection of the cold neutral gas, the negative ion count rate, N_i , by the proposed technique is equal to $N_i = n_a V_{\text{REL}} S_d \epsilon_c \eta_T \epsilon_d$, where n_a is the neutral atom local number

density; V_{REL} is the spacecraft velocity relative to the neutral gas; S_d is the instrument effective sensitive area; ϵ_c is the conversion efficiency; η_T is the efficiency of negative ion collection and transmission through the magnetic analyzer; and ϵ_d is detection efficiency by the TOF section of the instrument. Instrument parameters may vary widely and for such realistic values as $V_{REL} = 75$ km/s, $S_d = 1$ cm², $\epsilon_c = 10^{-2}$, $\eta_T = 0.5$, and $\epsilon_d = 10^{-1}$, one obtains a sensitivity $N_I/n_a = 4 \times 10^3$ (count s⁻¹)/(particle cm⁻³), and the overall efficiency of the instrument, $\epsilon_c \eta_T \epsilon_d$, to detect individual atoms would be 5×10^{-4} . Such a sensitivity is sufficient to detect interstellar H, D, and O atoms while noise count rate being suppressed by coincidence requirements in the TOF section.

Presently the instrument described here is an idea and extensive laboratory study is required to transform it to flight instrument concept. It seems also unlikely that such an instrument can be built within the limits of 1 kg and 1 W. The reduction of the size and weight of the instrument can be achieved by replacing the magnetic analyzer by a small broom magnet to remove electrons from negative ion flux. Ion mass identification still would be possible by the TOF section allowing the detection of interstellar hydrogen and oxygen atoms. Only laboratory study can show what is the best to implement the proposed technique.

3. Measurement of the HELENA flux.

The goal of the experiment is to measure velocity distribution function of the HELENA's. It is expected that the energy of HELENA's would be in the 100-800 eV range, the flux would be highly anisotropic with intensity up to $(2-3) \times 10^2$ cm⁻² s⁻¹ sr⁻¹ keV⁻¹ from the upwind direction [Gruntman, 1992].

A proposed scheme of the sensor, which is similar in some aspects to the one described for the study of interstellar plasma [Gruntman, 1993b], is shown in fig.4. It is important that the size of the sensor (without a simple baffle) is only $4.5 \times 2 \times 2$ cm. The sensor's field-of-view is 10^{-2} sr (about 6.5° in one dimension) and entrance diameter is 10 mm. The sensor includes a high transparency grid, G, two thin carbon foils, TF₁ and TF₂, followed by a microchannel plate (MCP) detector, D, after 2 cm flight length. The thin foil TF₂ is biased at -10 KV, detector sensitive surface is at -2 KV and detector's anode/collector is

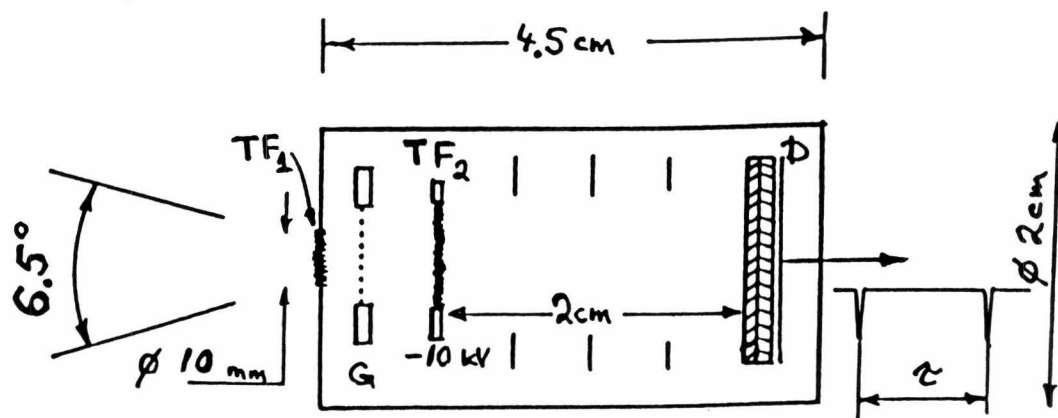


Fig.4. Scheme of the sensor to study low-energy heliospheric ENA's. G - grid, TF₁ and TF₂ - thin foils, D - microchannel plate detector.

conveniently at the ground potential. A baffle contains an electrostatic deflection system that removes ions with energies < 30 keV. Some physical phenomena, relevant to the envisioned application and occurring when ENA penetrates a thin foil, are briefly summarized in accompanying paper by *Gruntman, 1993b*.

The first foil, TF_1 , strips of HELENA's which emerge from the foil with a certain probability as positively charged ions. The stripping probabilities for low-energy hydrogen atoms were measured by *Overbury et al., 1979*. When a positive ion enters the sensor, it is additionally accelerated up to 10 keV, hits the thin foil, penetrates it, and continues its flight toward the detector, D. Secondary electrons, forward emitted from the foil, are accelerated by 8 kV voltage between the foil and detector, overtake the ion, and reach the detector first producing a START pulse for the time-of-flight (TOF) analyzer. Then the ion reaches the detector and produces a STOP pulse. Hence, the ion detection results in appearance of a pair of pulses from the detector (coincidence) and a time interval between the pulses is determined by the ion energy. Since the initial energy of HELENA's (< 1 keV) is much smaller than the acceleration energy (10 keV), the time intervals between pulses are well determined. This scheme of the TOF analysis, which is called a single-channel TOF scheme (as opposed to the widely-used two-channel TOF scheme when START and STOP pulses are generated by two separate, independent detectors) is very rarely used in instruments [e.g. *Gruntman and Morozov, 1982; Gruntman, 1983,1989*]. It requires a rather special arrangement of the TOF electronics and careful dealing with the ringing and afterpulses but allows building of exceptionally small, compact, and simple sensors. Details of the performance characteristics as well as discussion of the advantages and limitations of the single-channel scheme can be found in [*Gruntman and Morozov, 1982; Gruntman, 1983,1989*].

Depending on the charge state of the particle after the foil, the particle proceeds to the detector (fig.4) with either constant velocity (neutral particle) or acceleration (negative ion) or deceleration (positive ion). Consequently, the detection of the HELENA's will produce two peaks in the TOF spectrum corresponding to the neutral and negatively charged states after the foil. The energy of the positively charged ions after the foil is not sufficient to reach the

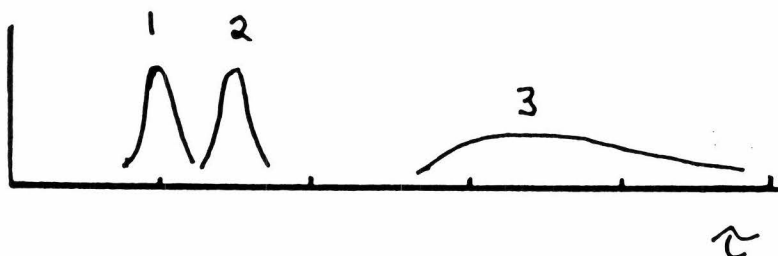


Fig.5. Expected TOF spectrum for the detection of HELENA's. Peaks 1 and 2 are produced by HELENA's that are stripped during the passage of the foil TF_1 ; peak 1 and correspond to negatively charged and neutral particles after the foil TF_2 . Peak 3 correspond to HELENA's that remain neutral after passage of the both foils.

detector due to the energy loss in the foil. Figure 5 shows schematically the expected TOF spectrum with peaks 1 and 2 corresponding to negatively charged and neutral particles after the foil. With a small probability, a HELENA particle would remain neutral penetrating both foils

and produces secondary electron from the foil TF_2 . Such particles would produce a broad peak in the TOF spectrum (peak 3 in fig.5) which is directly related to the initial energy distribution of HELENA's. The detection of this peak by a similar single-channel TOF sensor has been successfully demonstrated by [Gruntman and Morozov, 1982].

Background photon flux (mostly Ly-alpha) is responsible for the noise counts and random coincidences of the TOF scheme. The count rate of random coincidences (TOF events) is very important for the detection of very weak ENA fluxes. The geometrical throughput of the sensor, $10^{-2} \text{ cm}^2 \text{ sr}$, limits the photon flux into instrument to $10^3 \times F_R$ photons per second (F_R is the photon flux in Rayleighs). The background Lyman-alpha flux at 100 AU from the Sun is about 20 R and forward photoelectron emission yield from the foil is known [Hsieh et al., 1980]. The use of two foils would efficiently suppress the count rate due to the background photons. Estimates show that the overall background count rate of detector will be only several counts per second and the coincidence count rate would be less than 10^{-4} s^{-1} . The use of the TOF scheme eliminates also effect of other sources of noise counts such as MCP detector intrinsic noise and count rate due to the RTG.

The performance characteristics of a single-channel TOF scheme is usually limited by the minimum time interval which is possible to measure between two pulses. This results in a limit on the maximum possible particle energy that can be registered. In the instrument of Gruntman and Morozov, 1982, this interval was 16-17 ns and it was achieved using electronic components commercially available in the end of 1970s. Presently it is possible to reduce this limit down to 10 ns and maybe even less. This limitation can be also easily overcome by decreasing the acceleration voltage at the thin foil or increasing the flight length.

The presented scheme of the compact TOF sensor would allow direct measurement of the HELENA's on the Interstellar Probe mission. The use of only one MCP detector results in exceptionally compact design which minimizes the power consumption as well. The reliability of the proposed sensor is similar or better than that of much bigger in size "standard" two-channel TOF schemes. Combination of the presented detector scheme with the novel baffle design (Gruntman, to be published, 1993) should allow one to achieve (and hopefully to surpass) the requirement of 1 kg and 1 W.

Preliminary study shows that the possibility exists to combine this sensor with the small plasma sensor described in the accompanying paper [Gruntman, 1993b]. The combined versatile detector (IONA - ION and Neutral Atom detector, Gruntman, 1993, unpublished) can find wide application at various future deep space missions (e.g. Pluto Fast Flyby) requiring small size instruments.

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