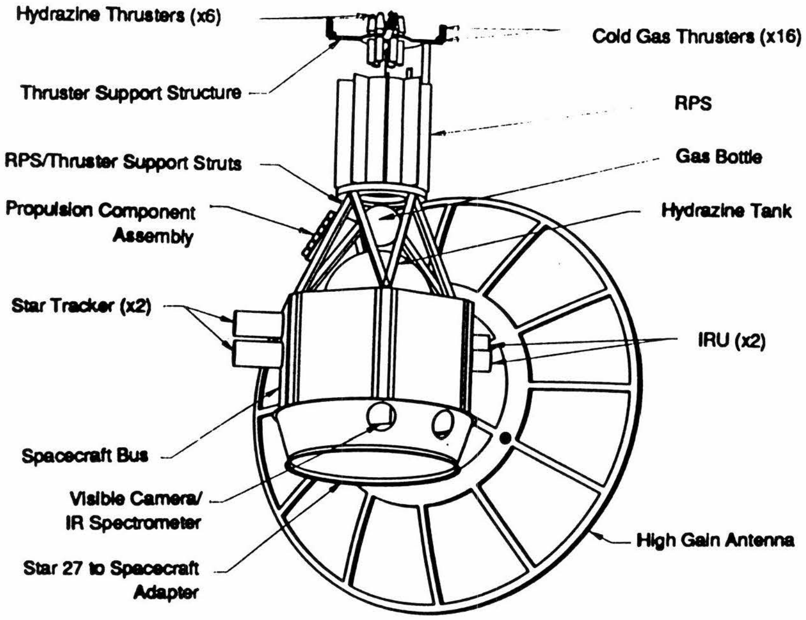
SMALL INSTRUMENTS FOR SPACE PHYSICS

PROCEEDINGS OF THE SMALL INSTRUMENT WORKSHOP HELD IN PASADENA, CALIFORNIA, 29-31 MARCH, 1993*

EDITED BY B.T. TSURUTANI



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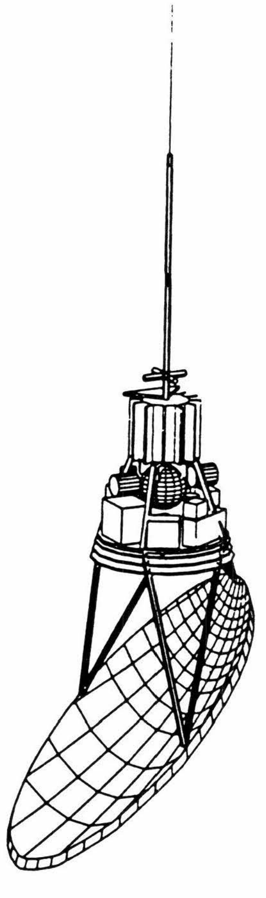

The Small Solar Probe

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November 1993

*The Workshop and efforts in producing this book were sponsored by
Space Physics Division, National Aeronautics and Space Administration, Washington, D.C.

A SIMPLE INSTRUMENT TO MEASURE THE COMPOSITION OF INTERSTELLAR PLASMA DURING THE INTERSTELLAR PROBE MISSION

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ABSTRACT

The Interstellar Probe mission is a unique opportunity to measure characteristics of the local interstellar medium *in situ* and direct study of the interstellar plasma will be in the focus of such a mission. A simple compact sensor capable of measuring the ion composition of the interstellar plasma is proposed. It consists of a microchannel plate detector and thin foil and utilizes a single-channel time-of-flight technique. The suggested configuration fits ideally the conditions of measurements performed at large distances from the Sun. The proposed scheme will allow the measurement of the number density of protons, deuterium, helium, carbon, and oxygen ions as well as ions of heavier elements.

I. Introduction

Our star, the Sun, is surrounded by the local interstellar medium (LISM) which is characterized by a small but finite pressure. The expanding supersonic flow of the solar wind interacts with the LISM forming the heliosphere (fig.1). We do not accurately know the characteristics of the LISM and the shape and size of the heliosphere. Moreover the physics of the LISM, which contains partially ionized interstellar gas, cosmic rays and magnetic field, is poorly understood [e.g. *Frisch, 1990*]. The Interstellar Probe mission would present a unique opportunity to send a spacecraft directly into the LISM (fig.1) unperturbed by the presence of the Sun (> 100-150 AU) and to study it *in situ*. Obviously the study of the interstellar plasma will be in the focus of such a mission.

Budgetary constraints resulted in a substantial downscaling of the proposed Interstellar Probe mission and a realistic scientific payload would probably be in the range of 10-15 kg rather than the initially planned 105 kg [*Space Physics Missions Handbook, 1991*]. Consequently, exceptionally compact instruments will be required for this and other future deep space missions. This paper describes a concept of a very compact, flashlight-battery-size sensor to measure the composition, velocity and temperature of the interstellar plasma in the LISM. Similar sensors can be flown on other missions where a compact and light-weight instrument is a must for inclusion in the scientific payload. A Pluto Fast Flyby mission is as an example of a possible application of the proposed sensor where it can measure the planet's ionosphere composition as well as obtain characteristics of various populations of ions and energetic neutral atoms during the cruise phase.

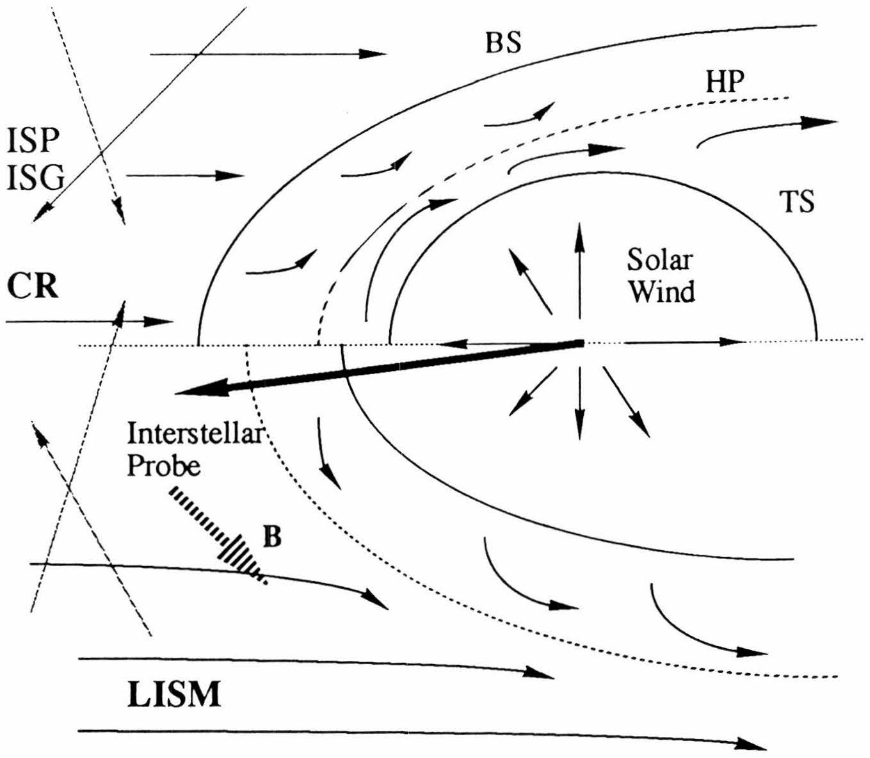

Fig. 1. Interaction of the solar wind with the local interstellar medium. The structure above the axis corresponds to the supersonic flow of the interstellar plasma; below the axis - to the subsonic flow. LISM - local interstellar medium; TS - termination shock; HP - heliopause; BS - bow shock; CR - cosmic rays; ISP (G) - interstellar plasma (gas); B - magnetic field. The trajectory of the Interstellar Probe is close to the upwind direction.

2. Interstellar Plasma

After crossing the termination shock and heliopause, the Interstellar Probe spacecraft will enter the LISM (fig. 1). Characteristics of the interstellar plasma in the LISM are not accurately known, and one can expect them to be in the range:

number density: n_e = $(5 \times 10^{-3} - 5 \times 10^{-2})\ \text{cm}^{-3}$
temperature: T = $(5\text{-}12) \times 10^3$ K
bulk velocity: V_{plasma} = 20-28 km/s

It is interesting that for the expected number density and temperature of the plasma the Debye length would be 50-100 m. The goal of the plasma experiment on the Interstellar Probe will be to determine these plasma characteristics as well as its composition.

The most abundant component of the interstellar plasma is expected to be protons since atomic hydrogen constitutes about 90% of the interstellar gas (ISG). As far as minor components are concerned, their abundances depend on the composition of the ISG, the history of the portion of Galaxy surrounding the Sun, and physical processes in the LISM. One can expect to find a wide variety of different elements in the interstellar plasma, most of them being singly charged. For example in the Sun, the following elements (only the most abundant isotopes are shown) have abundances larger than 10^{-6} of that of hydrogen:

element	amu	element	amu
H	1	Ne	20
D	2	Na	23
He	4	Mg	24
C	12	Al	27
N	14	Si	28
O	16	S	32
		Ar	40
		K	39
		Ca	40
		Cr	52
		Mn	55
		Fe	56
		Ni	58

The species above are divided into two groups: "light" ions (left) and "heavy" ions (right). The technique proposed here will be capable of identifying the light ions only. The heavy ions will be detected but their mass will not be identified.

It is expected that the velocity, V_{SC}, of the Interstellar Probe spacecraft will be about 50 km/s (10 AU/year). The plasma velocity relative to the spacecraft, $V_{plasma} + V_{SC}$, will be about 75 km/s which corresponds to the energy of 29.1 eV/nucleon. This means that ions enter the instrument with energies, for example, 29, 58, 116, 349, and 466 eV for atomic ions of hydrogen, deuterium, helium, carbon, and oxygen correspondingly.

The interstellar ions would come into the instrument from slightly different directions due to ion thermal velocities. Figure 2 shows the dependence of the ion fluxes on the angle for different ion species which are characterized by the same temperature. One can see that practically the entire flux of oxygen ions is confined within a 5° angle while protons are confined within an angle of about 15°. These dependencies determine the requirements for the instrument field-of-view.

3. Instrument

A proposed scheme of the sensor is shown in fig.3. It is important that the size of the sensor (without a simple baffle) is only 4.5 × 2 × 2 cm. The sensor's field-of-view is 6×10^{-3} sr (about 5° in one dimension) and its entrance diameter is 3.5 mm (sensitive area 0.1 cm^2). The sensor includes a high transparency grid, G, a thin carbon foil, TF, followed after 2 cm flight length by a microchannel plate (MCP) detector, D. The thin foil is biased at

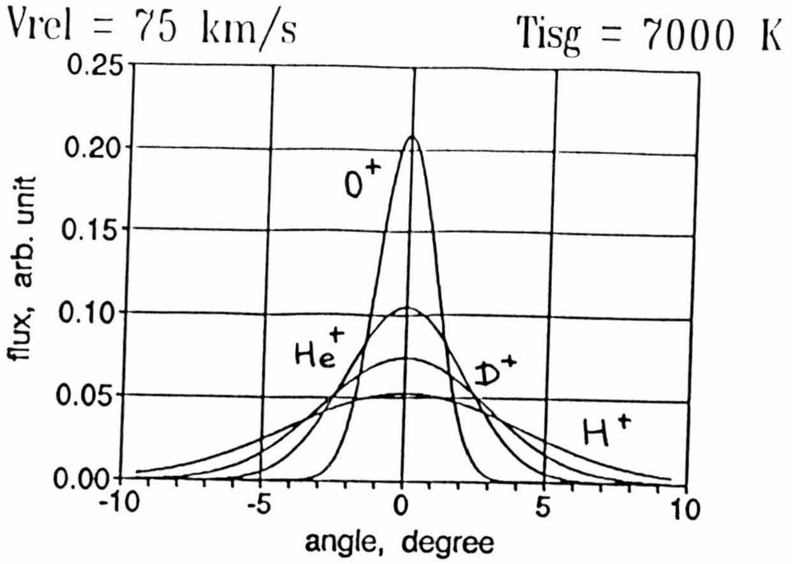

Fig.2. Angular dependence of the interstellar ion flux for H+, D+, He+, and O+. The plasma temperature is 7000 K; the velocity relative to the spacecraft is 75 km/s.

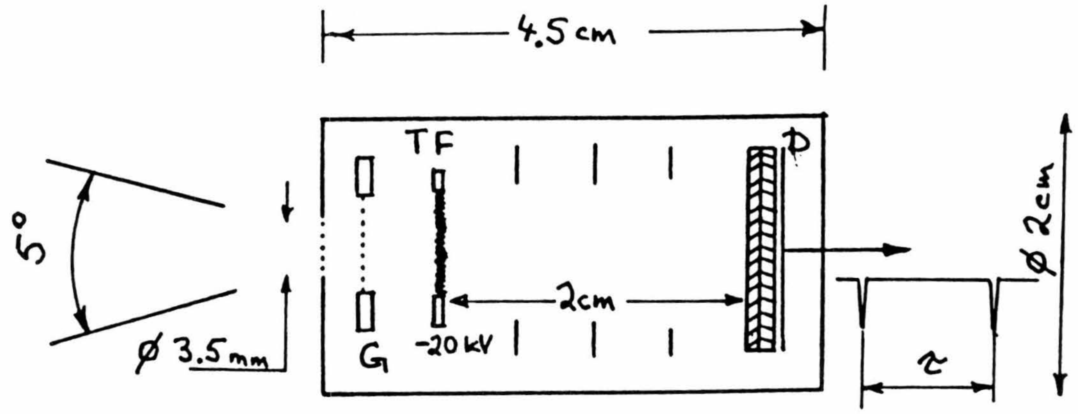

Fig.3. Scheme of the sensor to study the composition of the interstellar plasma. G - grid; TF - thin carbon foil; D - microchannel plate detector.

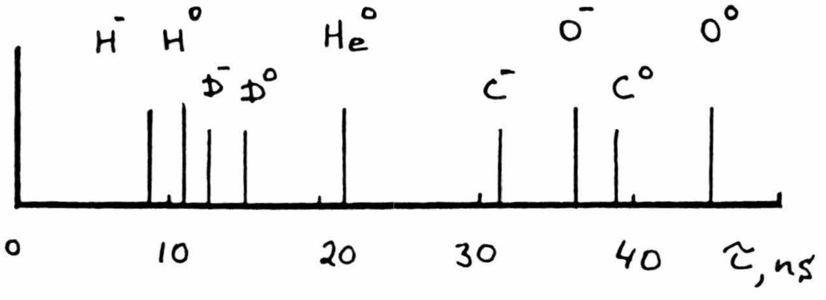

Fig.4. Calculated TOF peaks corresponding to different species for the sensor shown in fig.3.

— 20 KV, the detector sensitive surface is at — 2 KV and detector's anode/collector is conveniently at the ground potential.

Let us summarize the important characteristics of a self-supporting thin (50-250 Å) carbon foil relevant to our application. When an energetic ion impinges on and penetrates such a foil several physical effects occur:

1. Energy loss.
   Part of the ion energy is lost in the foil. Since the process of particle penetration (straggling) and energy loss is a statistical process, the energy loss fluctuates from ion to ion. As a result, a monoenergetic ion flux impinging on the foil will be transformed to a flux with a wide energy distribution after the foil.
2. Scattering.
   Ion trajectories are changed after foil passage due to the scattering.
3. Change of charge state.
   The charge state of the particles after the foil is a combination of positively charged ions, neutral atoms, and negatively charged ions (providing the latter can exist). The distribution of particle charge states after the foil does not depend on the particle charge state before the foil but it does depend on particle mass, energy and foil material.
4. Electron emission.
   Electrons are emitted from the foil, in both the forward and backward directions, due to passage of the ion.

When a positive ion enters the sensor, it is accelerated up to 20 keV, hits the thin foil, penetrates it, and continues its flight toward the detector, D. Secondary electrons emitted forward from the foil are accelerated by the 18 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 the appearance of a pair of pulses from the detector (coincidence) and the time interval between the pulses is determined by the ion mass. By measuring the TOF spectrum, one can determine the mass spectrum of the registered ions. This scheme of the TOF analysis, which is called a single-channel TOF scheme (as opposed to the widely-used two-channel TOF scheme where 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 [e.g. *Gruntman, 1989*] but allows building 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] and *Gruntman* [1989].

The dependencies of the probability of ion charge states on the particle type and energy were measured by several groups [e.g. *Burgi et al., 1990; Funsten et al., 1992*]. Depending on the charge state of the particle after the foil, the particle proceeds to the detector (fig.3) with either constant velocity (neutral particle) or acceleration (negative ion) or deceleration (positive ion). Consequently, the detection of the ions of a certain species, for example protons, will produce two peaks in the TOF spectrum corresponding to the neutral and negatively charged

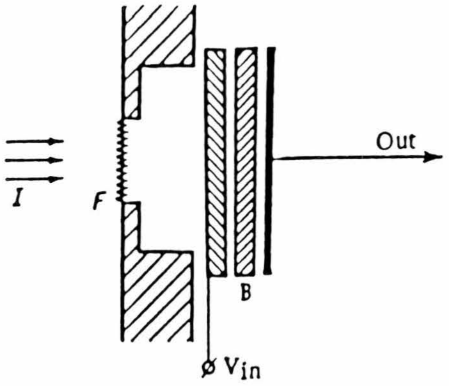

Fig.5. Schematic of the detector-energy analyzer. F is a carbon foil 80 Å thick; I are H^+, H_2^+, and He^+ ions, and B is a block of microchannel plates. (From *Gruntman, 1983*)

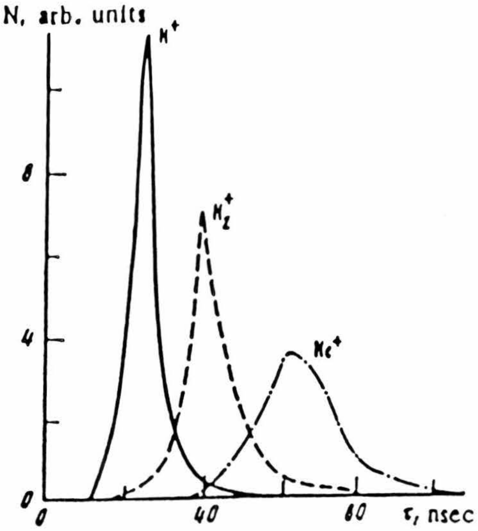

Fig.6. Time-of-flight spectra obtained during detection of 3-keV H^+, H_2^+, and He^+ ions. (From *Gruntman, 1983*)

states after the foil. The energy of the positively charged ions after the foil is not sufficient to reach the detector due to the energy loss in the foil. Figure 4 shows positions of TOF peaks fordifferent species for the sensor shown in fig.3. Due to the variations in ion energy losses, the TOF peaks will actually look like broad humps rather than like δ-functions.

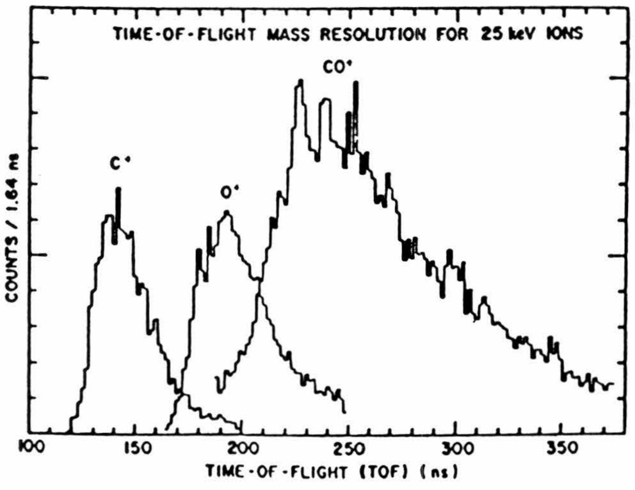

Fig.7. Timing resolution for 25 keV C^+, O^+, and CO^+ in the TOF telescope. (From *Gloeckler and Hsieh, 1979*)

The proposed single-channel TOF scheme has been successfully demonstrated for the detection of either ions [*Gruntman, 1983*] or energetic neutral atoms [*Gruntman and Morozov, 1982*]. The sensor setup is shown in fig.5 and figure 6 demonstrates its performance when detecting H^+, H_2^+ (which simulated D^+), and He^+ ions [*Gruntman, 1983*]. The partial overlapping of the TOF peaks was due to the low energy (3 keV) of ions. Acceleration of the ions up to 20 KV (as suggested in fig.3) would completely separate these peaks. Figure 7 demonstrates that ions of carbon and oxygen of about the same energy, 25 keV in this particular case, can be also successfully separated [*Gloeckler and Hsieh, 1979*]. Although *Gloeckler and Hsieh* [1979] used a "standard" two-channel TOF scheme, a single-channel TOF scheme performance will be similar and carbon and oxygen peaks will be separated.

The performance of a single-channel TOF scheme is usually limited by the minimum time interval which it is possible to measure between two pulses. This results in a limit on the maximum possible particle energy that can be registered. In the instruments of *Gruntman and Morozov* [1982] and *Gruntman* [1983] this interval was 16-17 ns and it was achieved using electronic components commercially available in the end of 1970s. It is presently possible to reduce this limit down to 10 ns and maybe even less. Since the limitation of the minimal measurable time interval affects only the detection of light ions (hydrogen and deuterium), it can be easily overcome by decreasing the acceleration voltage at the thin foil (preferably) or increasing the flight length. In any case this limitation does not present a serious problem for envisioned applications.

The overwhelming majority of the registered ions on the Interstellar Probe will be protons. The proton peak (its low-energy "tail") in the TOF spectrum may virtually bury small peaks corresponding to interstellar deuterium, carbon and heavier ions. If a voltage of about 40 V is applied to the grid, G, then the passage of the interstellar protons into the instrument would essentially be blocked while all heavier ions would be allowed to reach the thin foil and subsequently be detected. In this way the detrimental effect of the protons on the detection of minor species can be practically eliminated. Moreover, by slowly varying the voltage at the grid, G, and measuring the corresponding change of the proton signal (as in a retarding potential analyzer), one can determine both the velocity and temperature of the interstellar plasma.

The 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 such minor constituents as interstellar deuterium and oxygen. The small geometrical throughput of the sensor, 6×10^{-4} cm^2 sr, limits the photon flux into the instrument to $50 \times F_R$ 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 the forward photoelectron emission yield from the foil is known [*Hsieh et al., 1980*]. Estimates show that the overall background count rate of detector will be only few counts per second and the coincidence count rate 10^{-5} s^{-1}. The use of the TOF scheme also eliminates the effect of other sources of noise counts such as the MCP detector intrinsic noise and the count rate due to the RTG.

The overall sensitivity of the proposed sensor is about $(1\text{-}5) \times 10^5$ (count/s)/(ion/cm^3) which should allow the *in situ* detection of such minor species as ions of interstellar deuterium, carbon, and oxygen.

4. Conclusion

The presented scheme of the compact TOF sensor would allow direct measurement of the composition of interstellar plasma on the Interstellar Probe mission. Such important plasma parameters as temperature and bulk velocity will also be obtained. The use of only one MCP detector results in an exceptionally compact design which minimizes the power consumption as well. The reliability of the proposed sensor is similar to or better than that of much bigger "standard" two-channel TOF schemes.

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

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