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A NEW WAY TO MEASURE THE COMPOSITION OF THE INTERSTELLAR GAS SURROUNDING THE HELIOSPHERE

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ABSTRACT

The composition of neutral gas in the Local Interstellar Medium can be studied by direct, *in situ* measuring of interstellar neutral atoms penetrating into interplanetary space. A novel experimental approach for *in situ* atom detection, which has never been used earlier in space, is proposed. The technique is based on the conversion of neutral atoms to negative ions at a specially prepared sensitive surface. Negative ions are subsequently analyzed and detected in an essentially noise-free, multi-coincidence mode. It is shown that interstellar hydrogen, deuterium, and oxygen atoms can be measured by the proposed technique. The experiment can be performed from a high-apogee Earth-orbiting satellite or from a deep space probe.

INTRODUCTION

A study of the interstellar gas (ISG) from the local interstellar medium (LISM) is a source of unique information on the properties of the LISM, which surrounds our solar system. The study of the ISG should lead to a better understanding the processes of the interaction of the expanding solar wind flow with the LISM, building up of the heliosphere, and related phenomena. It is sometimes overlooked, that neutral gas is the most abundant constituent of the heliosphere. If one excludes the sun, planets, and other celestial bodies, then 98-99 % of the mass of matter filling the heliosphere is represented by the ISG and the remaining 1-2 % is the solar wind plasma. This work is devoted to the discussion of a new approach to measure *in situ* the composition of interstellar gas surrounding the heliosphere, i.e. to sample the ISG locally, from the solar system neighborhood, and not averaging over large astronomical distances. The proposed technique is sensitive to hydrogen, deuterium and oxygen atoms. Ideas presented here are the development of the approach first outlined consistently by Gruntman /1/.

A study of the composition of the ISG is a field of astrophysics which may provide critical evidence for Big Bang cosmology and the theory of stellar formation and evolution. An accurate measurement of the deuterium-to-hydrogen ratio in the ISG is of prime value and could potentially provide the most important constraints on Big Bang cosmology /2/. Interstellar atomic oxygen is of great interest for the theories of formation and evolution of the stars /3/. On the "local" scale, oxygen from the LISM is believed to contribute to the oxygen component of anomalous cosmic rays /4/. There is some evidence of the inhomogeneity of the gas in the ISG clouds /5/, and measurements of the local composition of the ISG could provide unique information on the homogeneity of the LISM. An expanding supersonic flow of the solar wind interacts with the LISM forming the heliosphere. Experimental data on the morphology of the heliosphere boundary are scarce and indirect. Most of our knowledge on the LISM properties is a result of the astronomical observations and study of the ISG flowing into the solar system. Astronomical measurements are, by their nature, not local and provide characteristics averaged typically over many parsecs /6/. Study of the inflowing ISG, until recently, was performed by optical, integral measurements and derived ISG characteristics were essentially model dependent (e.g. /7/). There is increasing evidence that the interaction of the neutral ISG atoms with plasma flows in the heliospheric interface should affect substantially the characteristics of the neutral atoms reaching the inner parts of the solar system /8/. By directly measuring various components of the ISG, one can hope to get an insight into the physical processes in the heliospheric interface.

Neutral ISG from the LISM penetrates our solar system and some interstellar atoms reach the Earth's orbit. This phenomenon presents naturally an opportunity to measure directly the interstellar atoms. Direct atom detection was recently spectacularly demonstrated for the first time by the GAS experiment on the Ulysses spacecraft where the instrument was capable of measuring the local velocity distribution function of interstellar helium atoms /9/. Direct detection of other species of interstellar origin should dramatically enhance our understanding of the properties of the LISM and its interaction with the solar system. For very low neutral particle number densities, less than 10^2 cm^{-3}, any conventional experimental technique based on electron impact ionization of the neutral atoms is not applicable. The idea behind the approach proposed here is to use an instrument sensitive to the flux of neutral particles instead of an instrument sensitive to the neutral particle number density. A small (few km/s) neutral gas velocity relative to the spacecraft would result in a large flux of atoms and molecules into the instrument. Then even a small overall detection efficiency of individual particles by the instrument should result in a very high instrument sensitivity to the neutral particle number density. The novel experimental approach is based on conversion (at a specially prepared surface) of incident neutral particles to negative ions and subsequent analysis and detection of the negative ions. The conversion on surfaces into negative ions for detection purposes was first suggested and demonstrated in /10,11/. The use of the neutral atom conversion to negative ions was first suggested for space application by Gruntman and Leonas /12/ and was recently evaluated in detail in /1/. Such an arrangement should provide extremely high sensitivity, 10^{-1} - 10^4 (count s^{-1})/(particle cm^{-3}), depending on species and experimental conditions, which is orders of magnitude better than in existing instruments. The technique would make possible the first *in situ* measurement of interstellar hydrogen atoms and such important ISG minor components as atomic deuterium and oxygen.

PENETRATION OF NEUTRAL ATOMS INTO INTERPLANETARY SPACE

Direct *in situ* measurements of the ISG could be performed from various types of spacecraft. We concentrate here on the estimate of the expected fluxes of interstellar atoms at the Earth's orbit. Let us assume that an observer moves together with the Earth around the Sun. The velocity of the ISG relative to the Sun is V_0 = 20 km/s and its vector is in the ecliptic plane (Figure 1). The ISG temperature "at infinity" is T_0 =0 and calculations of neutral particle flux characteristics are performed following the procedure given in /13/. The ratio of radiation to gravitational forces is assumed to be equal to 0.8, 0.4, and 0.0 for H, D, and O atoms while the ionization rate is 5×10^{-7} s^{-1} at 1 AU from the sun for all species. The direction of the arrival of an interstellar particle to the observation point at angle Θ is described by the angle χ between the atom relative velocity vector, $\mathbf{V}_{rel}$, and radius-vector **R** (Figure 1). The dependence of the atom relative velocity, V_{rel}, and angle of arrival, χ, on the angle Θ is shown in Figures 2 and 3 respectively. The dependence of the fluxes of interstellar H, D, and O atoms (normalized to the corresponding fluxes in the unperturbed ISG far from the sun) on the angular position, Θ, is shown in Figure 4. The spread of the angles at which atoms are coming to a given point would be determined by the ISG temperature. The important result of the calculations (Figures 2-4) is that expected fluxes (cm^{-2} s^{-1} sr^{-1}) of different interstellar atoms depend in different ways on position and direction of the observation. This fact provides a basis for the unambiguous determination of the composition of the ISG from measurements performed at the Earth's orbit.

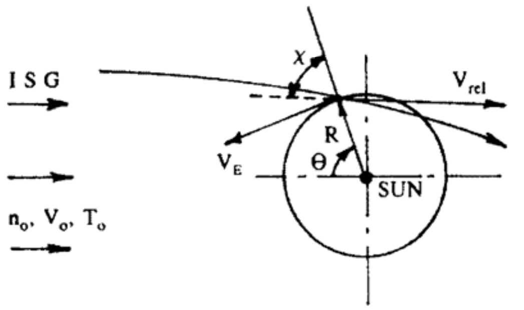

Fig. 1. Interstellar atom trajectory in the interplanetary space. $\mathbf{V}_{rel}$ is the velocity relative to an observer moving with the Earth ($\mathbf{V}_E$) along its orbit around the Sun. χ is the angle between the atom velocity $\mathbf{V}_{rel}$ and the radius-vector **R**, Θ is the angle between the upwind direction and **R**.

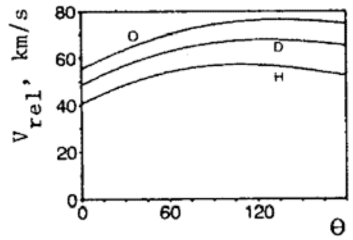

Fig.2. Dependence of velocity V_{rel} relative to the observer moving with the Earth on the angle Θ for interstellar H, D, and O atoms.

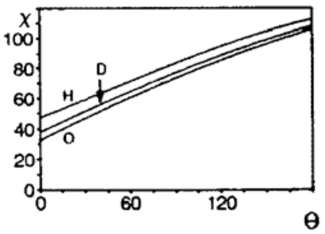

Fig.3. Dependence of the angle χ between relative velocity vector, $\mathbf{V}_{rel}$, and radius-vector, **R**, on the angular position along the Earth's orbit, Θ, for interstellar H, D, and O atoms.

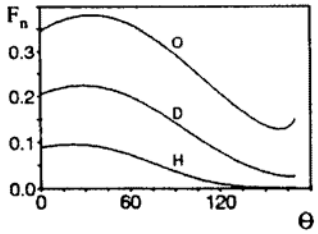

Fig.4. Dependence of the fluxes, F_n, of interstellar neutrals (normalized to flux in unperturbed ISG far away from the Sun) on the angular position Θ along the Earth's orbit.

NEW DETECTION APPROACH AND INSTRUMENT CHARACTERISTICS

For a realistic number density of hydrogen atoms in the LISM, $n_H = 0.1$ cm^{-3}, one can expect that atom number densities of deuterium, n_D, and oxygen, n_O, would be 10^{-6} and 10^{-4} cm^{-3} correspondingly. The new 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 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 has been well developed in laboratory applications, e.g. /14,15/. The general scheme for the detection and analysis of neutral particle fluxes is presented in Figure 5. 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 TOF analyzer for final detection. The TOF section provides an assured, essentially noise-free detection 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.

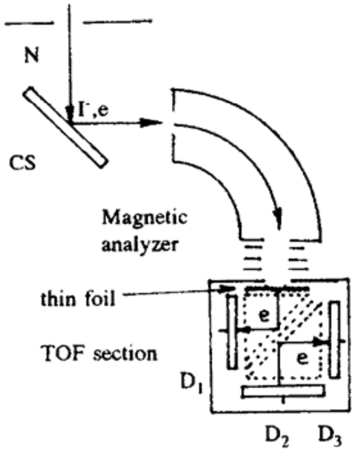

Fig.5. General scheme for detection and analysis of neutral atom fluxes. N - neutral atom; I^- - negative ion; CS - conversion surface; D_1, D_2, D_3 - microchannel plate detectors.

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. Atom conversion to negative ions is generally described by electron tunneling to the classically-moving atom /14,15/. 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 and some of them show promising characteristics, in particular complex multi-component cesium oxide mixture $Cs/Cs_2O/Cs_2O_2$, 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 $N_I = n_p V_{REL} S_d \varepsilon_c \eta_T \varepsilon_d$, where n_p is the neutral particle 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 $V_{REL} = 50$ km/s, $S_d = 1$ cm^2, $\varepsilon_c = 10^{-2}$,

$\eta_T = 0.5$, and $\varepsilon_d = 10^{-1}$, one obtains a sensitivity $N_I/n_p = 2.5\times10^3$ (count s^{-1})/(particle cm^{-3}), and the overall efficiency of the instrument, $\varepsilon_c\ \eta_T\ \varepsilon_d$, to detect individual atoms to be 5×10^{-4}. For the instrument intercepting all flux of the ISG atoms, this value of the detection efficiency would then result in typical count rates of 10, 2×10^{-4}, and 4×10^{-2} s^{-1} for interstellar H, D, and O atoms respectively, with noise count rate being suppressed by coincidence requirements in the TOF section.

The dynamic characteristics of expected fluxes of interstellar atoms at the Earth's orbit and the new experimental approach should allow us to measure unambiguously for the first time the composition of the ISG in the LISM. The best possible place to perform measurements of the ISG composition is from a fast moving interplanetary spacecraft or from an Earth orbiting spacecraft with a high apogee orbit. A number of other applications of the technique can be presently identified and they include the studies of i) neutral atoms in the sun's vicinity, ii) the flux of heliospheric energetic neutral atoms (HELENA's) born in the heliospheric interface region, iii) the tenuous neutral particle environment of planets, their moons, comets, and asteroids, iv) neutral gas evaporated from the small comets, v) oxygen atoms at the Earth's upper atmosphere and exosphere.

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