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ANISOTROPY OF THE ENERGETIC NEUTRAL ATOM FLUX IN THE HELIOSPHERE

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Abstract—Characteristics of the energetic neutral atoms born at the heliospheric interface are considered for plasma flow structure resulting from a two-shock model of the interaction between the solar wind and the interstellar medium. The energy distributions of heliospheric energetic neutral atoms (HELENAs) are calculated and it is shown that the HELENA flux is highly anisotropic at the Earth's orbit. The characteristics of the HELENA flux are highly sensitive to the size of the heliosphere. This supports the conclusion that measurements of HELENAs from the Earth's orbit would give us an efficient tool to remotely study the heliosphere.

INTRODUCTION

The interaction of the Sun and the local interstellar medium (LISM) is manifested by the build up of a heliosphere (e.g. Axford, 1990). The heliosphere provides a unique opportunity to study in detail the only accessible example of a commonplace astrophysical phenomenon—the formation of an astrosphere. From a practical point of view, the heliosphere is our natural "environment" and knowledge of its characteristics is important for the interpretation of space experiments, e.g. measuring cosmic rays (McKibben, 1990).

Direct experimental data on the heliosphere are quite limited. Direct proofs of the adequacy of our concepts of the heliosphere are not available, and its size and shape are not accurately known. A self-consistent model of the heliosphere has still to be built and many important parameters such as cosmic ray pressure and magnetic field in the LISM are known with poor accuracy.

The solar wind is a highly supersonic plasma flow into the LISM which is characterized by a certain finite pressure. It is believed that this supersonic plasma flow terminates at a solar wind shock front beyond which its kinetic energy is largely converted into thermal energy in the subsonic plasma. Details of this interaction depend essentially on the assumed parameters of the LISM. Neutral interstellar gas atoms penetrate relatively freely through the interface region, but there is a certain probability for "hot", energetic (> 100 eV) protons to charge exchange there with interstellar gas atoms and give rise to heliospheric energetic neutral atoms (HELENAs). The velocities of these particles would reflect the velocity distribution of the ions, and some of them would be directed "back" towards the Sun. Therefore HELENAs are probably the only messengers born beyond the solar wind termination shock and capable of reaching the inner solar system with a minimum disturbance. At present the imaging of the heliosphere in the HELENA fluxes seems to be the only means to remotely study, from the Earth's orbit, the distant boundaries of the heliosphere. Remote study will remain important even if a spacecraft, e.g. *Voyager* 1, one day crosses the termination shock. Only a remote technique can provide a global view of the heliosphere on a continuous basis.

The measurement of HELENA particles, which has yet to be demonstrated, presents a challenging experimental task. A discussion of all the relevant experimental problems is beyond the scope of this paper. It only has to be mentioned here that the instrumentation, developed initially for the study of the neutral solar wind (Gruntman and Morozov, 1982; Gruntman *et al.*, 1990), is capable of measuring and performing energy analysis of very weak fluxes of low energy hydrogen atoms (< 1000 eV) in the presence of the dominant u.v./e.u.v. background radiation. The use of similar instrumentation for the measurement of the HELENAs, and thus of the heliosphere itself, was first suggested by Gruntman and Leonas (1983) and the first attempt to perform such measurements is planned on the *Relikt*-2 mission (Gruntman *et al.*, 1990). The development of recently suggested novel e.u.v. photon suppressing filters (Gruntman, 1991) may make the measurements less difficult in the newly proposed instrumentation. Requirements for a dedicated space experiment and instrumentation to perform the imaging of the heliosphere in HELENA fluxes from the Earth's orbit were discussed recently by Hsieh *et al.* (1990), Curtis *et al.* (1990) and Gruntman (1990).

Expected characteristics of the HELENA flux have never been previously presented in detail. The value of the total expected HELENA flux (10^2 cm^{-2} s^{-1}) and the average atom velocity were just mentioned by Bleszynski (1987) as a by-product of his Monte Carlo study of the filtering of interstellar gas at the heliopause. Such flux values can also be obtained easily from rather simple qualitative considerations (Gruntman, 1990). However, the discussion of a dedicated space experiment and optimization of the relevant instrumentation require knowledge of the expected HELENA flux characteristics in much more detail.

The HELENA flux should also be responsible for some of the noise count rates of u.v. photometers on board the *Pioneer* 10/11 spacecraft which measure the interplanetary glow at the hydrogen (1216 Å) and helium (584 Å) resonance lines (Carlson and Judge, 1974). This source of noise may become important as the intensity of backscattered radiation decreases with *Pioneer* 10 moving away from the Sun (the spacecraft is now at 50 a.u.).

The present work is devoted to the calculation of the energy distributions and the anisotropy of the HELENA flux at the Earth's orbit. All calculations are performed for plasma flow parameters determined by a two-shock model of the interaction of the solar wind and the LISM plasmas.

MODEL

Various scenarios of the interaction between the expanding solar wind and the LISM are possible depending on the solar wind plasma and the LISM parameters (e.g. Parker, 1961; Axford, 1972). For example, it is not known whether interstellar plasma flow is subsonic or supersonic. Similarly, the strength and the direction of the magnetic field in the LISM are not accurately known, nor is the cosmic ray pressure. A self-consistent model of the stationary heliosphere has not yet been built and there are good reasons to think that the heliosphere is "breathing", changing its size and shape during the solar cycle. All these factors can have a substantial effect on the morphology of the heliospheric boundary and parameters of the hot plasma which is a source of the HELENAs. However, the motion of the Sun relative to the LISM should result in an anisotropic heliosphere, compressed on the upwind side and extended in the wake direction.

It is assumed in this work that the interaction of the solar wind plasma flow and the interstellar plasma flow is described by the Baranov stationary two shock model (Baranov, 1990a,b). This model seems to be the most quantitatively developed at the moment though it has a number of inherent deficiencies. An important feature is, however, that the Baranov model provides plasma flow characteristics in a form which allows one to scale them for different parameters of the LISM and solar wind plasmas. The latter feature makes it a convenient tool for making the semiquantitative estimates. However, one has to keep in mind that the derivation of the heliosphere parameters from the measurements requires a detailed understanding of the physical processes involved and extensive computer simulation. In the Baranov model, both the interstellar plasma flow and the solar wind flow are supersonic and hence two shocks, bow shock and solar wind termination shock, are formed (Fig. 1). The plasma flow is cylindrically symmetric and angle Θ is measured from the direction antiparallel to the vector of the relative velocity of the interstellar plasma flow. Only the plasma parameters in the region where the HELENAs are born, i.e. between the heliopause and termination shock, are of interest for the scope of the present work. Most of the kinetic energy of the solar wind plasma transforms into energy of thermal motion of the plasma ions and electrons beyond the termination shock.

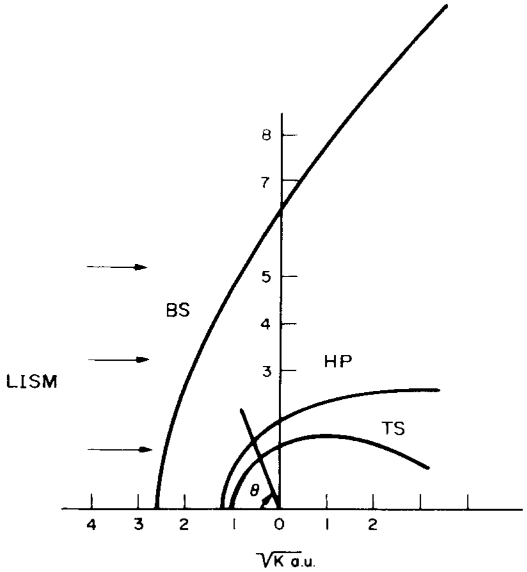

FIG. 1. TWO SHOCK MODEL OF THE INTERACTION OF THE INTERSTELLAR PLASMA FLOW WITH THE SOLAR WIND.
BS is a bow shock, HP is a heliopause and TS is a termination shock. All dimensions are in the units of $\sqrt{K}$ a.u., and the definition of the factor K is given in the text.

Neither cosmic rays nor an interstellar magnetic field are included in the model which results in an increased size of the heliosphere. In this model, the characteristics of plasma flow in the interface region, i.e. the region between the bow shock and the termination shock, are calculated for a particular Mach number of the interstellar plasma flow. For a constant Mach number all linear distances, i.e. the distances from the Sun to the bow shock, the heliopause, and the termination shock, are scaled by a certain factor, $\sqrt{K}$. The factor K is equal to $N_{sw}V_{sw}^2/N_{isp}V_{isp}^2$, where V_{sw} and N_{sw} are the bulk velocity and the number density of the solar wind at the Earth's orbit and V_{isp} and N_{isp} are the bulk velocity and the number density of the unperturbed interstellar plasma, respectively. Both the solar wind and the interstellar plasma are assumed to consist only of protons and electrons. This possibility of scaling the plasma flow structure for different parameters of the solar wind and interstellar plasmas makes the Baranov model a convenient tool for semiquantitative estimates.

The characteristics of plasma flow used in this work were computed by Baranov (Baranov, V. B. pers. comm.) for an interstellar plasma flow Mach number equal to 1.6. The influence of neutral interstellar gas on plasma flow structure was neglected.

Let us assume that the entire interface region is filled with a neutral interstellar hydrogen gas with a uniform number density N_0. Hot plasma protons may charge exchange with neutral atoms and give rise to energetic hydrogen atoms, the HELENA flux. We will only consider the HELENA flux coming back to the Sun along the radial direction and reaching the Earth's orbit. HELENA particles are considered to move freely and effects of solar gravitation and solar radiation pressure are disregarded. Such an assumption seems to be justified because (i) for high velocity atoms the effect of acceleration in the gravitational field is relatively small compared with an atom's initial velocity and (ii) for low velocity atoms solar gravitational attraction is approximately counterbalanced by solar radiation pressure.

Let us consider HELENA flux coming sunward to the observation point at the distance of 1 a.u. from the Sun and situated at angle Θ (Fig. 1). HELENA particles are born in the charge exchange process along this direction in the region between the heliopause and the termination shock. Only those atoms with their velocity vector directed towards the Sun would reach the observation point. The velocity distribution of HELENA flux (per unit area), which is born in a unit volume at a distance R from the observation point, is

$$f(V_A) = N_0\sigma(V_A)V_A g(V_A)S(V_A)/R^2,$$

where V_A is the velocity of a HELENA particle and $\sigma(V_A)$ is the charge exchange cross-section. The dependence of the charge exchange cross-section $\sigma(V_A)$ on the relative velocity of the colliding particles is approximated by the formula of Maher and Tinsley (1977). The distribution function (per unit solid angle) of plasma protons is given by

$$g(V_A) = N_P\left[\frac{M}{2\pi k_b T_P}\right]^{3/2} V_A^2 \times \exp\left[-\frac{M(V_A-U_R)^2}{2k_b T_P} - \frac{MU_N^2}{2k_b T_P}\right]$$

and corresponds to a shifted Maxwellian distribution, where k_b is the Boltzmann constant, M is the proton mass, $N_P = N_P(R)$ and $T_P = T_P(R)$ are the number density and temperature of the plasma protons, and $U_R = U_R(R)$ and $U_N = U_N(R)$ are the proton velocity components in the radial and azimuthal directions, respectively. The plasma flow parameters N_P, T_P, U_R, and U_N depend on both R and Θ and were computed by Baranov, V. B. (pers. comm). The function $S(V_A)$ is a survival probability for a neutral hydrogen atom with a given velocity to reach the observation point, i.e. the Earth's orbit ($R_E = 1$ a.u.), moving radially towards the Sun. It can be shown that

$$S(V_A) = \exp(-\beta_0 R_0^2/V_A R_E),$$

where β_0 is the hydrogen atom ionization rate (photoionization plus charge exchange with solar wind ions) at the distance R_0 from the Sun. The dependence of S on the hydrogen atom energy is presented in Fig. 2

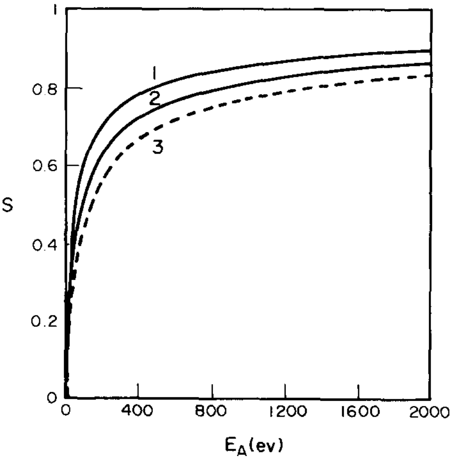

FIG. 2. ENERGY DEPENDENCE OF THE PROBABILITY S OF A NEUTRAL HYDROGEN ATOM TO REACH A POINT 1 a.u. FROM THE SUN FOR DIFFERENT ATOM IONIZATION RATES: (1) $\beta_0 = 4.5\times10^{-7}$ s^{-1}; (2) $\beta_0 = 6.0\times10^{-7}$ s^{-1}; (3) $\beta_0 = 7.5\times10^{-7}$ s^{-1}.

for different ionization rates. We will assume that the average ionization rate at the Earth's orbit is 6×10^{-7} s^{-1}.

The velocity distribution of the total HELENA flux (per unit area and per unit solid angle) reaching the observation point is given by the integral over the line of sight between the termination shock and the heliopause

$$F(V_{\rm A}) = \int_{R_{\rm TS}}^{R_{\rm HP}} f(V_{\rm A}) R^2 \, {\rm d}R.$$

Making transformation from the velocities of HELENAs to the corresponding energies, which is more convenient for the presentation of the present results, one finally obtains the expression for the energy distribution of HELENA particles (cm^{-2} s^{-1} sr^{-1} erg^{-1})

$$F(E_{\rm A}) = \frac{2MN_0 E_{\rm A}\sigma(E_{\rm A})S(E_{\rm A})}{(2\pi M)^{3/2}} \int_{R_{\rm TS}}^{R_{\rm HP}} \frac{N_{\rm P}}{({\rm k_b}T_{\rm P})^{3/2}} \times \exp\left(-\frac{E_{\rm A}+E_0 \pm 2(E_{\rm A}E_{\rm R})^{1/2}}{{\rm k_b}T_{\rm P}}\right){\rm d}R,$$

where $E_0 = M(U_{\rm R}^2 + U_{\rm N}^2)/2 = E_0(R)$ and $E_{\rm R} = MU_{\rm R}^2/2 = E_{\rm R}(R)$ are proton energies corresponding to the plasma total bulk velocity and the velocity component in the radial direction (the negative sign in the argument of the exponential corresponds to a radial velocity directed towards the Sun, and the positive sign corresponds to the anti-solar direction). Total HELENA flux, F_0 (per square centimeter per second per sterodian), would consequently be equal to the integral over the energy distribution

$$F_0 = \int_0^{\infty} F(E_{\rm A}) \, {\rm d}E_{\rm A}.$$

It is also convenient, as discussed later, to use the total flux of HELENAs with energies greater than 400 eV, i.e.

$$\int_{E_{\rm min} = 400 \, {\rm eV}}^{\infty} F(E_{\rm A}) \, {\rm d}E_{\rm A}.$$

RESULTS AND DISCUSSION

The calculated HELENA energy distributions are presented in Fig. 3 for different angles Θ. Parameters used in the present calculations are: $N_0 = 0.1$ cm^{-3}; $V_{\rm sw} = 500$ km s^{-1}; $N_{\rm sw} = 5$ cm^{-3}. Solar wind characteristics (correspond to the conditions 1 a.u. from the Sun. The interstellar plasma velocity is $V_{\rm isp} = 20$ km s^{-1}, number density $N_{\rm isp} = 0.04$ cm^{-3}, and the temperature is 11,275 K, which corresponds to a Mach number of 1.6. The intensity of HELENA flux is scaled by the interstellar hydrogen atom number density. The dependence of the total HELENA flux, F_0, on Θ is shown in Fig. 4. The dependence of the flux of HELENA with an energy greater than 400 eV is also presented in Fig. 4. The detection efficiency of neutral atoms is about 0.01 at $E_{\rm A} = 600$ eV and it decreases rapidly with decreasing atom energy (Gruntman and Morozov, 1982; Gruntman *et al.*, 1990). An atom energy $E_{\rm A} = 400$ eV could probably be considered as an energy threshold for the neutral particle detection as currently envisaged. Therefore the value of $F_0(E_{\rm A} > 400 \text{ eV})$ is useful for the assessment of the feasibility of an experiment to measure the HELENA flux.

Not only does the total flux intensity diminish with

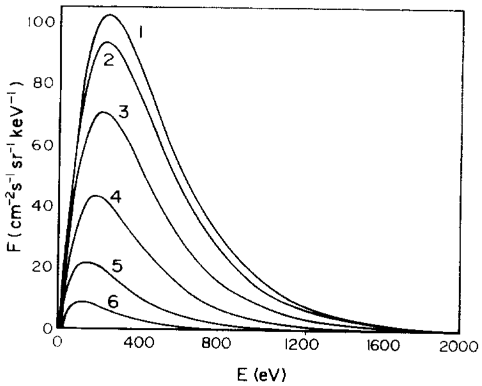

FIG. 3. ENERGY DISTRIBUTIONS OF THE HELENA FLUX FOR DIFFERENT ANGLES Θ; SOLAR WIND VELOCITY (AT 1 a.u. FROM THE SUN) IS CONSTANT $V_{\rm sw} = 500$ km s^{-1}; (1) 0 ; (2) 18 ; (3) 36 ; (4) 54 ; (5) 72 ; (6) 90 .

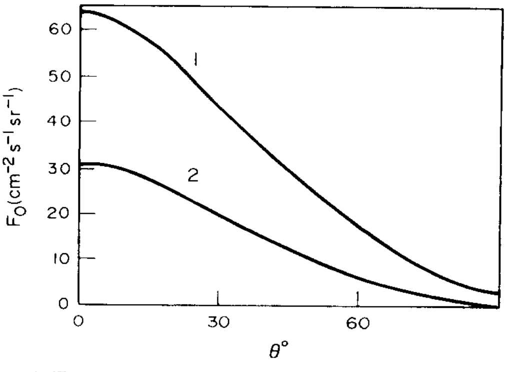

FIG. 4. TOTAL (INTEGRATED OVER ENERGY) HELENA FLUX F_0 (CURVE 1) AS A FUNCTION OF THE ANGLE Θ. Curve 2 is flux of HELENAs with atom energy greater than 400 eV.

increasing Θ (towards the wake), but also the energy distributions shift to smaller energies. This happens because both the radial and angular components of the plasma bulk velocity increase and, simultaneously, the plasma temperature decreases as the angle Θ increases. It is important to note that a change of the interstellar plasma velocity and/or number density would result in a change of the size of the heliosphere and the total HELENA flux. However, the shape of the HELENA energy distribution would remain unchanged for the Baranov plasma flow model.

The HELENA flux coming from the wake region of the Sun is virtually non-existent. The *Pioneer* 10 spacecraft is moving away from the Sun in the wake region, its u.v. photometer is looking in the anti-solar direction, and for all practical purposes the effect of the HELENA flux on detector count rate can be neglected.

For the parameters of the interstellar plasma and the solar wind used in this work, the distances from the Sun to the termination shock and heliopause are $R_{TS} = 264$ a.u. and $R_{HP} = 352$ a.u., respectively, for $\Theta = 0$. There are indications that the size of the heliosphere should be substantially smaller than that given by the Baranov model (e.g. Webber, 1987). The interstellar plasma number density used was $N_{isp} = 0.04$ cm^{-3}, and one way to simulate a high "outside" pressure of cosmic rays and an interstellar magnetic field is to increase the value of N_{isp}. Strictly speaking, such an increase is not equivalent to the actual outside pressure because the pressure of cosmic rays has to be isotropic and the pressure of the interstellar plasma flow is highly directional. However, one can expect that at least in the upwind direction, the conditions at the interface region would be similar to those expected for the presence of an additional outside isotropic pressure. Figure 5b demonstrates the dependence of the size of the heliosphere in the upwind direction ($\Theta = 0$) on the interstellar plasma number density. As has already been mentioned, in the two shock model the shape of the HELENA energy distribution has to remain unchanged for different interstellar plasma flow parameters and consequently for different sizes of the heliosphere. The total HELENA flux, F_0, would be different for different values of N_{isp}, and the dependence of F_0 on the interstellar plasma number density is shown in Fig. 5a for $\Theta = 0$. One can clearly see that the closer the solar wind termination shock is to the Sun, the higher the expected HELENA flux. The termination shock located at a realistic distance of about 100 a.u. from the Sun in the upwind direction corresponds to an interstellar plasma number density equal to 0.3 cm^{-3} in the model used. Though such interstellar plasma number density is unrealistically high, one could expect that the two shock model gives conditions in the heliospheric interface similar to those expected for a more realistic number density (say, $N_{isp} = 0.04$ cm^{-3}) and additional pressure of the cosmic rays and the interstellar magnetic field. For the termination shock located at a distance of 100 a.u. from the Sun the total expected HELENA flux is equal to 150 cm^{-2} s^{-1} sr^{-1} and approximately half of the atoms would have an energy greater than 400 eV.

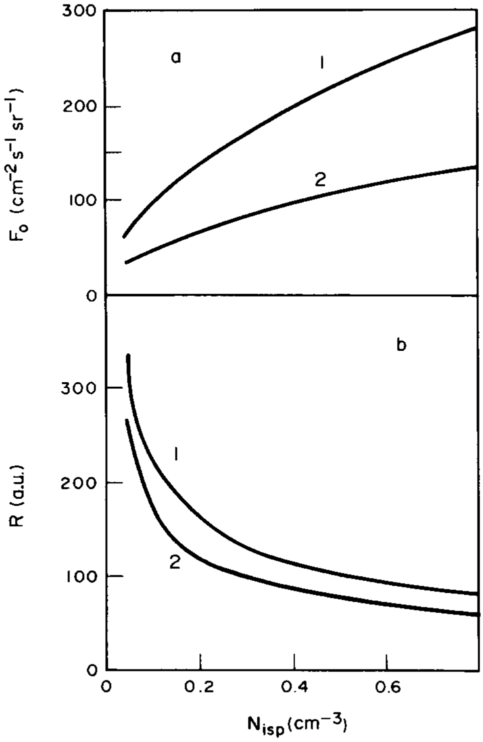

FIG. 5. (a) DEPENDENCE OF THE TOTAL FLUX OF HELENAS (1) AND FLUX OF HELENAS WITH THE ENERGY GREATER THAN 400 eV (2) ON NUMBER DENSITY OF THE INTERSTELLAR PLASMA FOR $\Theta = 0$.

(b) Dependence of the position of the heliopause (1) and the termination shock (2) on the number density of the interstellar plasma ions for $\Theta = 0$.

Figure 6 demonstrates the dependence of the HELENA energy distributions on the solar wind velocity at 1 a.u. from the Sun for $\Theta = 0$. The solar wind number density is maintained constant. The bulk of the energy distributions shifts towards higher energies with an increase of the solar wind velocity and the high energy tail of the distribution grows rapidly.

HELENAs are born in the heliospheric region containing hot plasma and they are expected to reach an observer at 1 a.u. from the sun with negligible disturbance. Measurement of the HELENA flux and its energy distribution should provide information on

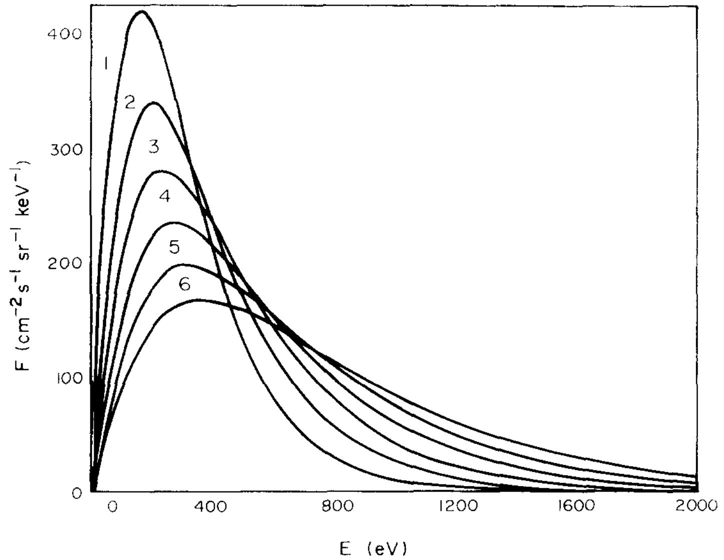

FIG. 6. ENERGY DISTRIBUTIONS OF THE HELENA FLUX FOR DIFFERENT SOLAR WIND VELOCITIES (AT 1 a.u. FROM THE SUN) V_{sw}; ANGLE $\Theta = 0$; (1) 400 km s^{-1}; (2) 450 km s^{-1}; (3) 500 km s^{-1}; (4) 550 km s^{-1}; (5) 600 km s^{-1}; (6) 650 km s^{-1}.

the parameters of the hot plasma beyond the termination shock. How much one can learn from such measurements about the properties of the LISM and the heliosphere boundary morphology remains an open question. A definitive answer requires extensive computer simulation supported by the development of a self-consistent model of the heliosphere, including non-stationary effects. However, some conclusions can be made now on the basis of the semiquantitative estimates presented here.

Detection of the HELENA flux would provide an unambiguous signature of the existence of the termination shock, which has yet to be proved experimentally. HELENA flux intensity measurements should give us the distance between the termination shock and the Sun, and HELENA energy distribution data could provide the value of plasma temperature in the interface region. Asymmetry of the HELENA flux could elucidate a number of questions. Dependence of HELENA flux characteristics on the angle Θ may provide an answer as to whether the interstellar plasma flow is subsonic or supersonic as well as to the value of the isotropic pressure outside the heliosphere. Variations of the HELENA flux in latitude, i.e. the difference between HELENA parameters in and out of the ecliptic plane, would contain information on the large scale, global anisotropy of the solar wind. Asymmetry of the HELENA flux parameters relative to the vector of the solar system motion through the LISM could provide information on the magnetic field strength and direction in the LISM. It takes different time intervals for HELENA particles with different energies to reach the Earth's orbit. For example, it takes two and a half years for a HELENA with 200 km s^{-1} velocity to travel from hot plasma at a distance of 100 a.u. from the Sun, and it takes only one and a half years for a HELENA with 300 km s^{-1} velocity. Therefore even a single measurement of the energy distribution of the HELENA flux may yield information about the heliosphere "history", i.e. heliosphere "breathing" and the corresponding temporal variations at the heliospheric interface. Feasibility of the extraction of physical information from such measurements, which involves non-trivial deconvolution, could be determined only on the basis of the self-consistent heliosphere model which has yet to be developed.

The energy distributions of the HELENA flux presented here are highly sensitive to the size of the heliosphere and parameters of the interstellar plasma and solar wind, and we have shown that the HELENA characteristics are highly anisotropic. This justifies the optimism that measurements of HELENA from the Earth's orbit would give us an efficient tool to remotely study the distant boundaries of the heliosphere.

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