Determination of the direction of the interstellar medium motion relative to the Sun by measurements of interstellar pickup ion helium

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Abstract. One of the main methods to measure the direction of the interstellar medium flow relative to the Sun is to measure parameters of interstellar pickup helium atoms at the Earth orbit or at its nearest neighbourhood. Pickup ions are formed in the interplanetary medium through photoionization of interstellar helium atoms. Charge exchange in the region of interaction of the solar wind with interstellar medium no effect on distribution of the atoms. Thus, the helium ions in the inner regions of the heliosphere carry information about the interstellar medium, and measurements of charged particles on spacecraft are much simpler than neutral atoms directly. Here, however, when one try to determine the direction of the interstellar flow exactly, some problems of “transport” nature can occur. These problems can sometimes result in unexpected “discoveries”. All these aspects are discussed in the paper.

Introduction
The local interstellar medium (LISM) surrounding the Sun is partially ionized gas, which according to current knowledge moves with the relative speed of about 26.3 km s\(^{-1}\). The main LISM components are hydrogen atoms, while the number density of protons is at least twice less. The collision of the supersonic solar wind with the interstellar flow gives rise to an interaction region, which includes the internal (termination) and external shocks at which the solar wind and the interstellar medium, respectively, decelerate, and the heliopause that separates the charged components of the both medium. It charged components responsible for the formation of the shock waves since mean free paths of the interstellar atoms are comparable to the size of the heliosphere and it is determined mainly by charge-exchange between hydrogen atoms and protons. The charge-exchange has a great influence on the structure of the interaction region and on physical processes in the outer heliosphere. For instance, as a result of the charge-exchange, the supersonic solar wind decelerates and heats up, the termination shock and the heliopause approach the Sun [1]. In addition, a specific very “hot” population of interstellar pickup ions is formed in the heliosphere, which in many respects changes thermodynamic properties of the solar wind [2].

The region inside the heliopause is a kind of a filter for the interstellar atoms with a large charge-exchange cross section (hydrogen, oxygen). But the interstellar helium atoms penetrate almost freely into the inner heliosphere since the charge-exchange process can be ignored. Thus, measurements of atomic helium parameters on spacecraft near the Earth’s orbit can give important information about “pure” LISM, without invoking complex multidimensional numerical models of the heliosphere.
The only force that affects the motion of helium atoms is the gravitational attraction of the sun, since the radiation pressure is negligible. The clear manifestation of the solar attraction is the gravitational focusing of helium atom. The focusing results if formation of a region of enhanced atomic density of helium. This region is located on the downwind side of the Sun and is called the gravitational focusing cone (figure 1).

![Figure 1. Gravitational helium cone is shown schematically in the ecliptic plane.](image)

In the inner heliosphere helium atoms undergo photoionization. As a result, helium ions (pickup ions) are formed. Usually it is once ionized atoms He+. Since the local production rate of pickup ions is proportional to the atomic density, in addition to the gravitational cone of helium atoms, a similar structure consisting of pickup helium ions must exist. One can expect that the positions of the density maxima and the geometric sizes for the two structures are identical. However, as was pointed out in [3], the deviation of the pickup-ion velocity distribution from an isotropic one can cause a relative angular displacement between the charged and neutral helium cones. Below we discuss this effect in more detail.

**Pickup ion transport**

1.1. Spatial distribution of helium atoms

In general, numerical models are needed to describe precisely the parameters of the helium atoms through the heliosphere. For some purpose, however, it is sufficient to use simple analytical models. The simplest one is the so-called cold model in the frame of which interstellar atoms are considered as a flow of neutral particles with zero temperature. Up to the moment of ionization atoms follow planar hyperbolic orbits under the action of gravitational attraction. The spatial distribution of the atoms in the interstellar flow \( V_∞ \). If \( \Phi \) is the off-axis angle then the impact parameters identifying a direct and indirect orbit which pass through the point \( r, \Phi \):

\[
p_{1,2} = \left\{ \left( \frac{1}{2} r \sin \varphi \right)^2 + \frac{r}{C} (1 + \cos \varphi) \right\}^{1/2} \pm \frac{1}{2} r \sin \varphi.
\]

In the frame of the cold model, the number density of interstellar helium atoms in the heliocentric system of coordinates is given by [4]
where \( n_\infty \) is the helium number density in the LISM, \( P_{\text{loss}}(\nu) \) is the ionization rate at 1 AU, \( C = V_\infty^2 / GM \), \( G \) is the gravitational constant, \( M \) is the mass of the Sun.

Equation (2) gives the spatial distribution of helium atoms rather precisely, however, for positions far enough away from the downwind focusing cone only. It is not correct near the cone since it gives an infinitely large density of particles at its axis. This effect is connected with the fact that the thermal velocities of atoms were not taken into account. In [5] a modified cold model for helium atoms in the heliosphere was proposed. The model takes into account thermal spreading of trajectories near the axis of the cone. In the frame of the modified model the number density is given as before by equation (2) at \( \phi > \phi_c \), where \( \phi_c \) is the half angle of the focusing cone:

\[
\varphi_c = \frac{2}{3} \left( \frac{2k_B T_\infty}{\pi m V_\infty^2} \right)^{1/2}.
\]

Here \( T_\infty \) is the temperature helium in the LISM, \( m \) is the mass of the atom, and \( k_B \) is the Boltzmann constant. For angles \( \varphi \leq \varphi_c \), assuming Maxwellian velocity distribution atoms in the LISM, authors of [5] obtained

\[
\frac{n(r, \varphi)}{n_\infty} = \left( \frac{\pi GMm}{rk_B T_\infty} \right)^{1/2} \exp \left[ -\frac{\nu_e^2 P_{\text{loss}}(\nu_e) (\pi - \varphi)}{V_\infty^2 p_1} \right] + p_2^2 \exp \left[ -\frac{\nu_e^2 P_{\text{loss}}(\nu_e) (\pi + \varphi)}{V_\infty^2 p_2} \right],
\]

where

\[
D = \frac{2\pi m V_\infty^2}{27k_B T_\infty}.
\]

1.2. Properties of helium pickup ions

Interaction of the pickup ions with solar wind electromagnetic fluctuations results in pitch-angle scattering. At the initial moment in the solar wind rest frame the motion of pickup ions originating in the region of the neutral helium cone is the of gyration and streaming along a magnetic field line towards the Sun. However, in the case of weak scattering this velocity distribution is anisotropic and the bulk of the ions move towards the Sun. This effect leads to a systematic shift (in the ecliptic plane) of the pickup ion cone relative to the LISM velocity vector in the direction of motion of the Earth around the Sun (figure 2). The angle of the shift depends on the mean free path of ions parallel to the magnetic field line \( \lambda_\parallel \). At sufficiently low value of \( \lambda_\parallel \) when the velocity distribution is almost isotropic, the shift is absent.

All these effects can be described by the general transport equation for velocity distribution function of pickup ions. We will consider helium cone in the ecliptic plane. If \( V_{SW} \) is the solar wind speed, \( \Omega = 2.7 \times 10^{-6} \text{s}^{-1} \), components of the solar magnetic field are...
Here we use heliocentric spherical coordinate system \((r, \theta, \phi)\) with \(\theta = \pi/2\) (\(\theta\) — colatitude).

If we introduce the variable \(\chi = \cos \psi\), where \(\psi(r)\) is the angle between the vectors \(\mathbf{V}_{SW}\) and \(\mathbf{B}\), we obtain:

\[
b_r = \chi, \quad b_\phi = -\text{sign}(\chi)(1 - \chi^2)^{1/2}.
\]

Here \(b = B/B\). Then in the case of the outward pointing magnetic field

\[
\chi(r) = \left[1 + \left(\Omega r / V_{SW}\right)^2\right]^{-1/2}
\]

The differential equation for the velocity distribution function of pickup ions in the ecliptic plane can then be written in the following form:

\[
\frac{\partial f}{\partial t} + (V_{SW} + v\mu \chi) \frac{\partial f}{\partial r} - \frac{v \mu}{r} \left(1 - \chi^2\right)^{1/2} \frac{\partial f}{\partial \phi} + \left[1 - 3\mu^2 1 - \chi^2 2 r \mu - \mu^2 \right] V_{SW} v \frac{\partial f}{\partial v} = \hat{S}f + Q(t, r, \phi, v, \mu).
\]

In equation (7) \(v\) and \(\mu = \cos \xi\) are the speed and the cosine of the ion pitch angle \(\xi\) in the solar wind rest frame. Note that equation (9) written for nonstationary case to make it easier to imagine the
general form of this equation, while we consider everywhere here only stationary solutions. The right hand side of the equation contains the scattering operator $\hat{S}$ applied to function $f$, and the source term, which describes the influx of freshly ionized particles. The scattering operator describes pitch-angle scattering of pickup ions by solar wind fluctuations and velocity diffusion (see details in [6]).

![Graphical representation](image)

**Figure 3.** Spatial distributions of pickup ions in the helium focusing cone near the axis of symmetry in the ecliptic plane at 1 AU. Different curves correspond to different values of the parallel mean free path: 0.1 (nearly isotropic velocity distribution), 0.3 and 1 AU (highly anisotropic distribution).

**Numerical results**

The authors of [7] have analyzed data from various spacecraft at different times on the interstellar wind flowing through the heliosphere. They concluded that temporal changes in the ecliptic longitude of the flow direction with time statistically indicated by the data available in the refereed literature at the time of paper writing. The data based on the measurements of pickup helium focusing cone in 2000 with the ACE and in 2010 with the STEREO spacecraft. For these events, the shift cone in longitude is a few degrees in the direction of increasing. The authors explain this shift by the turbulent nature of the interstellar cloud that surrounds the heliosphere. There are, however, another more natural way of explanation of the shift. In 2000, solar activity was near maximum, while in 2010 the spacecraft was in extended solar minimum conditions, beginning in 2007. The transport of charged particles, as mentioned earlier, essentially depends on the solar activity. Near maximum, the level of electromagnetic fluctuations in the solar wind is high, pitch-angle scattering of ions is very effective and, as a result, the mean free path of these ions is low. Under minimum solar wind conditions, the picture is opposite.

Figure 3 shows the spatial distributions of pickup ions in the helium focusing cone near the axis of symmetry in the ecliptic plane at 1 AU. The distributions were obtained by solving equation (9) for different values of $\parallel\lambda$. The mean free path depends on the level of fluctuations in the solar wind, which determine the value of the scattering operator $\hat{S}$ (see details in [6]). For small value of $\parallel\lambda$, the velocity distribution function of pickup ions is close to isotropy and positions of the neutral helium and pickup cone axis are coincides (no shift). During solar minimum (quiet solar wind) $\parallel\lambda$ is large and the velocity distribution function is highly anisotropic. In this case one can expect a large angular shift of the pickup helium cone axis relative to neutral helium cone axis in the direction of the Earth’s movement around the Sun.

Figure 4 shows the same as figure 3 but at different distances from the Sun: 0.3, 0.5 and 1 AU. In addition, the figures differ in the scale on the x-axis. Nearly isotropic distributions with $\parallel\lambda = 0.1$ AU
(dashed curves) and highly anisotropic ones with $\lambda_0 = 1$ AU are shown. Number density of pickup ions increases with approach to the sun due to the increase of the neutral helium number and increasing the frequency of photoionization.

![Anisotropic distribution](image)

**Figure 4.** Spatial distributions of pickup ions in the helium focusing cone near the axis of symmetry in the ecliptic plane at 0.3, 0.5 and 1 AU. Different values of $\lambda_0$ are used: 0.1 (dashed curves) and (solid curves).

**Conclusions**

We demonstrate in the present paper that attempts to use focusing cone consisting of the helium pickup ions should be performed with great caution. The fact that the axis of symmetry of this cone is different from the axis of symmetry of the atomic cone, which determines the direction of the interstellar wind. Due to transport effects pickup ion cone shift relative to atomic cone in the direction of the Earth’s movement around the Sun. The value of the shift is several degrees and depends on the solar activity.

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