III. Interaction of the Heliosphere with Interstellar Gas

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III.1 Solar Wind Interstellar Pickup Ion Interaction

As we have seen already material thrown into the solar wind is a marker for its dynamics. Comets led to its discovery. In these cases neutral gas and dust are thrown into the solar wind. Dust ultimately also loses more neutral gas because of evaporation. The neutrals feel the solar UV radiation, are ionized and then swept away with the solar wind. At this point I would like to tell a little story of my own about an exciting discovery relevant to this neutral gas - solar wind interaction. It led to the first direct observation of interstellar gas particles, and it all started with the search for the signatures of a Comet, a man-made comet!

A) Discovery of Pickup Ions

To start the story I have brought a little sound piece on this special man-made comet, a lithium cloud, thrown into the solar wind by evaporation of Li from the AMPTE (Active Magnetospheric Particle Tracer Explorers) IRM (ion Release Module) spacecraft.

Tape

The situation: ***View III.0***

The satellite sits in the cloud and the solar wind is trying to push the cloud away with its interplanetary magnetic field. We were prepared to study the effects of this gas cloud in the solar wind

a) to find out about cometary interaction with the solar wind
b) to trace solar wind particles into the magnetosphere (like the radioactive tracer techniques used in medicine)

with in-situ diagnostics

The instruments monitoring the effects were
a magnetometer
an electron and ion plasma instrument
a wave experiment (like a very sensitive radio receiver) -> sound
and the time-of-flight (TOF) mass spectrometer SULEICA

Let us start with the sound: What you hear in the beginning and at the end is the undisturbed solar wind, or more correctly the electromagnetic waves in the solar wind, as they are swept by the satellite. The varying magnetic fields of the embedded Alfvén waves (that we discussed in the previous chapter) produce varying electric fields that can be detected with the electric field antennas of the spacecraft. The varying fields are found in the frequncy range of sound. Therefore, they are audible when played through a loudspeaker. The abrupt silence comes from the Li cloud that blocks out the solar wind for a short time, as every comet does. Only a short time later the artificial comet is pushed past the spacecraft, and we hear the signature of the "bow shock" in front of the obstacle, where the magnetic field and the solar wind plasma gets piled up, a region with even stronger waves that were studied in detail with the wave experiment.

Let us now turn to the Li atome that were dumped into the solar wind. The TOF spectrometer SULEICA was built to distinguish different ion species in space plasmas and to derive their energy and angle distributions (= velocity distributions). The instrument is similar to the TOF spectrometer we discussed in the last chapter. A spherical section electrostatic analyzer is combined with a TOF section. Because the energies that we were looking for are high enough, we have no post-acceleration, but we have a solid state detector whose signal is proportional to the total energy of the incoming particle. So we get the energy E, the mass M and the ionic charge Q separately

View III.1

We were looking for Li ions to be accelerated by the solar wind out of the cloud.

- -> **identify them** (after ionization: Q = 1 -> M/Q = 7 in comparison with solar wind protons: M/Q = 1; or solar wind alpha particles: M/Q = 2)
- -> **get their direction** (They start with v = 0 and are accelerated, whereas the solar wind always blows with $v = V_{sw}$, a very cold wind, as we learned)

View III.2, 3

For the idealized situation of the IMF being perpendicular to the solar wind the motion of the newly born ions can be described as a cycloid (the motion at the periphery of a wheel that rolls on a surface) ***Demo Wheel***

The maximum velocity becomes

$$V_{max} = 2V_{sw}$$

when the point reaches the highest location on the wheel. If the IMF is at an angle Θ with respect to the solar wind, the maximum velocity along the direction of the solar wind becomes; $V_{max} = 2\sin\Theta\, V_{sw}$

In fact the newly born ion is moving perpendicular to B.

Searching for ions that move in the described way we found altogether **7 Li ions** out of $\approx 10^{25}$ atoms in the original cloud! ***View III.4***

This was somewhat disappointing, but the magnetic field direction was not right for most of the time to guide them into the instrument, which could only see particles coming into an acceptance angle of 40°. And more disappointing for the other team on the satellite in the magnetosphere, none were found in the magnetosphere!

However, sometimes the day of a negative result may be the lucky day! Simultaneously with the few Li ions we saw $^4He^+$ coming from the same directions as Li, and they were there also before and after the release. What was so exciting about this discovery? It had to be a natural source of neutral helium. This became clear immediately, since we were looking for ions that were the result of neutrals thrown into the solar wind. So we were not blinded for this discovery.

This is a **typical situation in research**.

We were looking for the right signature. Otherwise it might have been overlooked for some time. We were hunting for a different effect though, but we found a much more exciting result.

What are possible sources for neutral He?

a) **Earth's exosphere**
The Earth is exhaling He from radioactive material all the time, but measured He flux that we found was much too high (3 orders of magnitude)

b) **Interstellar gas**
From optical measurements it was known that interstellar He makes its way into the solar system and is found close to the sun.

And this was really exciting, since it was the first time to get in-situ measurements of interstellar gas, i.e., extrasolar material (except for high energy cosmic rays), not only material of our own solar system.

B) Evolution of Pickup Ion Distributions

How to make sense of the pick-up of these ions?
see *in Library Folder*

Möbius, E., D. Hovestadt, B. Klecker, M. Scholer, G. Gloeckler and F. M. Ipavich, Nature, 318, 426 – 429, 1985

Möbius, E., B. Klecker, D. Hovestadt and M. Scholer, Astrophys. Space Sci., 144, 487 – 505, 1988

We have learned that we measure the velocity distribution function of the ions with our instrument. We must now learn to interpret what the distribution function of the pickup He^+ ions means to understand, how we can derive the production rate of the ions from the neutral atoms and furthermore what the local neutral gas density is. If we have achieved this, we will have a result in hand from which we can derive the density of the interstellar gas outside of our solar system and much more.

This simplistic pickup scenario would suggest that we only see He ions coming from distinct directions (perpendicular to the magnetic field) and at very specific energies, as can be computed for the ion trajectories. Let us now us a trick that is always very useful: let us view the situation in the natural rest frame of physics, in this case the solar wind frame. Here the ions gyrate around magnetic field line and their gyrocenter moves along the field line with velocities:

perpendicular to B: $V_\perp = \sin\Theta\ V_{sw}$

parallel to B: $V_{||} = \cos\Theta\ V_{sw}$

Viewing the distribution in velocity space the ion distribution is a ring around the magnetic field vector with total velocity V_{SW}. ***View III.5***

Viewing this distribution with an instrument in the spacecraft frame, we would only see ions at a very specific energy, for example, for B perpendicular to V_{sw} ($\Theta = 90^o$) at the energy of 2 V_{sw} or 4 E_{sw} of He and along the solar wind direction.
However, we see ions coming into all sectors of the instrument, which are oriented towards the sunward hemisphere, no matter what the magnetic field direction is. ***View III.6***

For the sector in the solar wind direction the flux shows a plateau up to 2^*V_{SW}. i.e., the velocity space has been filled in direction and energy ***View III.7***
How does this happen?

Since the interplanetary magnetic field shows significant fluctuations, as we learned before, the ion trajectories are distorted randomly, i.e., the ions are scattered in direction, as seen in the frame of the solar wind. We will treat these transport processes again in more detail later. We will treat transport more rigorously, and we will also see that some of our simplifying assumptions are not completely valid. But the simple picture that we will draw still provides us with the basic physics. Let us take a heuristic approach for the time being: The scattering of particles at fluctuations of the IMF can be treated similar to "collisions" of particles. In this case the magnetic field with its fluctuations represents "particles" with a huge mass, let us assume an infinite mass. Now an elastic collision will alter the momentum of the incoming particle, but not the energy! Therefore, in the solar wind frame the energy of the He ions is conserved, they retain their full solar wind energy and speed V_{sw}, but they are scattered in direction. The resulting velocity distribution fills a hollow sphere in velocity space with velocity V_{SW} as its radius. ***View III.5a***

In the next step this distribution experiences the expansion of the solar wind. Like an expanding gas the distribution is cooled adiabatically, i.e., the hollow sphere shrinks as it moves away from the sun. Now new hollow spheres with the full radius (with velocity V_{SW}) are added. ***View III.8***
It should be noted here that we can take this step only in this simple way, if the scattering happens on a much faster time scale than the adiabatic cooling. In other words after transporting the pickup ions for a distance much shorter than the typical length scale of the cooling (which is $r_o \approx 1$ AU) there must be efficient scattering. Thus we get a mapping of the location where the He was ionized into the velocity distribution. The further the He had to travel from its origin (place of ionization) the smaller the sphere in velocity space. The measured speed v in the frame of the solar wind is directly related to the point of origin r by a function v(r):

$$(v(r)/V_{sw}) = (r/r_o)^{2/3}$$

or

$$(v(r)/V_{sw})^3 = (r/r_o)^2$$

The solar wind is expanding radially like r^2, i.e. the physical volume increases with the square of the distance. By adiabatic cooling the volume in velocity space shrinks accordingly, which leads to the above relation. In this case r_o is the point of observation (for a spacecraft in Earth orbit of course $r_o = 1$ AU) and r is the point of ionization. Therefore, the measured energy spectrum in the direction of the solar wind reflects this velocity distribution.
As it turns out the velocity distribution of pickup ions is a direct image of the distribution of the source of these ions along the spacecraft-sun line that can be written as:

$$f(v) = \frac{3 N_o (r(v)) v_{ion} \cdot r_o}{8\pi v_{sw}^4} \left(\frac{v}{v_{sw}} \right)^{-3/2} \qquad \text{(III.1\_1)}$$

This means, if we determine f(v) we can get $N_o(r)$, provided ν_{ion} is known. For comparison with the data we determine the differential flux according to (II.2_11).

$$\frac{dJ}{dEd\Omega} = f'(u,\theta,\phi)\frac{u^2}{m}$$

where u is the velocity in the S/C frame. $\vec{u} = \vec{v} + \vec{v}_{sw}$
According to these arguments the energy spectrum along the solar wind flow (which represents a radial cut through the velocity distribution in the solar wind frame) becomes an image of the original source distribution (or production rate) S(r) along the distance from the sun r. ***View III.18a***

The instrument collects ions in 1 sector ΔΩ over 1 energy step ΔE with

$$\Delta\Omega = \Delta\phi\cos\theta\Delta\theta \qquad and$$

$$\Delta E = mu\Delta u$$

where both are fixed values for a given instrument. I.e.

$$\frac{dJ}{dEd\Omega} = \frac{1}{\Delta\Omega\Delta E}\iint_{\Delta\Omega\,\Delta E} f'(u',\theta,\phi)u'^3\,du'\,d\phi\cos\theta\,d\theta$$

As ΔE varies as $\Delta E = E \bullet \left(\frac{\Delta E}{E}\right)$

where the relative resolution is constant, we use the differential energy flux density:

$$\frac{E\,dJ}{dE\,d\Omega} = \frac{E}{\Delta E\,\Delta\Omega}\iint_{\Delta\Omega\,\Delta E} f'(u',\theta,\phi)u'^3du'\,d\phi\cos\theta\,d\theta$$

If we use the normalized velocity, the distribution function f(w′) contains only u'/v_{sw}:
$$w' = u'/v_{sw}$$

$$\frac{E\,dJ}{dE\,d\Omega} = \frac{E\,v_{sw}^4}{\Delta E\,\Delta\Omega}\iint_{\Delta\Omega\,\Delta E} f'(w',\theta,\phi)w'^3\,dw'\,d\phi\cos\theta\,d\theta$$

In this way the measured quantity $\frac{E\,dJ}{dE\,d\Omega}$ is independent of the actual solar wind speed v_{sw}. Therefore, this quantity can be used as a measure of the neutral density independent of the variations of the solar wind, if it is measured in the solar wind direction. This is very useful, because the solar speed is quite variable, and usually we will have to integrate over long times to get enough counting statistics.

C) Ionization Processes

In order to determine the neutral density distribution N(r) from the pickup ion flux, we need to know the ionization rate ν_{ion}, because the pickup ion flux is the product of both. In addition, we will see that the ionization close to the sun also determines the spatial neutral gas distribution here. Ionization can occur through the following processes:

1) Ultraviolet ionization
→ To determine this contribution we have to measure the UV output of the sun for energies above the ionization potential of the respective species. This is now achieved on SOHO with the EUV monitor (SEM). Before that there were only a few rocket shots with such instruments available. For helium we get:

$$\nu_{ion} \approx 5 \cdot 10^{-8} - 2 \cdot 10^{-7}\ \sec^{-1}$$

depending on solar activity. ***Viewgraph SEM data***

2) Charge exchange with the solar wind

$$H^{+} + He \longrightarrow He^{+} + H$$

There is no momentum exchange, only a charge exchange! Therefore, the new ion keeps the velocity of the original neutral and vice versa. The ion generated through charge exchange cannot be distinguished from one that was generated by UV ionization. For He the contribution of this process is only ≈ 10%. However, for H charge exchange with solar wind protons is a resonant process with a large cross-section $H^{+}_{sw} + H \longrightarrow H^{+} + H_{sw}$ Therefore, this process is the most important one for H. ($\sigma_{chex} \approx 2 \bullet 10^{-15}\ cm^{2}$)

This process varies with the solar wind flux.
→ In order to determine its rate we have to measure the solar wind flux

3) Collisional ionization by electrons.

Solar wind electrons have temperatures of ≈ 10-50 eV. Thus a good fraction of these electrons contribute to ionization, which depends on solar wind density and electron temperature.

In general electron collisions provide only a minor contribution.

Note: Ionization does not only appear in

$$S(r) = N(r) \bullet \nu_{ion}(r)$$

it also determines N(r) in the vicinity of the sun.

ν_{ion} appears as production term for S(r) and as loss term for N(r)!

III.2 Interstellar Gas Flow through the Solar System

Determination of the Neutral Gas Density

see in Library Folder: Möbius, E., D. Rucinski, D. Hovestadt, B. Klecker, Astron. Astrophys., 304, 505 – 519, 1995

Let us talk about what we can learn from N(r) in the inner heliosphere. Ultimately we want to use pickup ions as messengers of the surrounding local interstellar medium (LISM). To derive the parameters outside we need to compute the distribution of the neutral gas inside the solar system as a function of the LISM parameters outside (N_o and T). This is a very interesting task, because the sun is moving w.r.t. the ISM.

Viewgraph

We see an interstellar wind coming in, like sitting in the driver's seat of an open car. The neutral gas density is not only decreased by ionization in the vicinity of the sun (which creates a void around the sun), it is also focused by the gravitational field of the sun on the downwind side. This works like gravitational lensing. This effect creates an immense opportunity to study the LISM:

The ratio

$$\frac{V_b^2}{GM_s} = \beta \qquad \text{(III.1\_3)}$$

determines the importance of the focusing effect and thus how strong it is. It has the dimension of an inverse distance. We can derive V_b from the gravitational effect, i.e. the relative velocity and its direction, if we can observe the effect. Looking at the trajectories we see that they merge on a line in the anti-solar direction.

For perfectly cold gas the density would become infinite here. A random velocity of the neutral gas will broaden the focusing cone, i.e., a high temperature T_o will wash out the structure. Therefore, we can also get T_o from such an analysis.

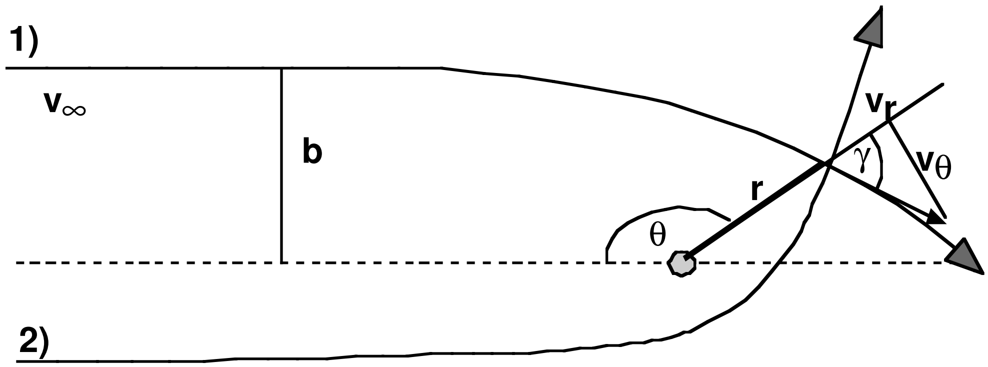
Let us now discuss the resulting spatial distribution of the interstellar neutral gas:

The LISM flow can be treated collisionless. We compare λ_{coll} for the neutral gas with the distance from the sun where gravitation becomes important, which is

$$r_{grav} = 2/\beta \qquad \text{(III.1\_4)}$$

$$\lambda_{coll} >> r_{grav}$$

i.e. we can treat the trajectories of neutral atoms as Kepler orbits (hyperbolae) in the gravitational field of the sun.



On the downwind side of the sun always 2 trajectories (1) and 2)) meet, the direct trajectory (1) and the indirect trajectory (2). A rigorous treatment of this Kepler problem can be found in: ***Danby, Camm, Mon. Not. Roy. Astron. Soc. 117, 50, 1957***

We define the following quantities:

b: collision parameter

$\vec{r}(r,\theta,\varphi)$: position where we take the measurement

The local velocity **v**(r,θ,ϕ) is determined by V_∞ (the velocity at infinity) and the gravitational field.

The problem is rotationally symmetric → There is no dependence on ϕ.

We define the angular momentum on the particle trajectory

$$bV_\infty = rv_\theta = rv\sin\gamma \qquad \text{(III.1\_5)}$$

Let us start with a cold gas T = 0, $v_\infty = v_b$.

Then with flux conservation:

$$N_\infty(v_b)\cdot 2\pi b\,db\cdot v_b = N(\vec{r},\vec{v})\cdot 2\pi r\sin\theta\,dr\cdot v\cdot\sin\gamma \qquad \text{(III.1\_6)}$$

or

$$\frac{N(\vec{r},\vec{v})}{N_\infty(v_b)} = \frac{b\cdot v_b}{r\sin\theta\cdot v\sin\gamma}\frac{db}{dr}$$

with (III.1_5) (angular momentum conservation)

$$\frac{N(\vec{r},\vec{v})}{N_\infty(v_b)} = \frac{1}{\sin\theta}\frac{db}{dr}$$

For Kepler motion we can use the parametric description of the orbits:

$$v = \frac{\beta b^2}{1+\beta b\sin\theta_i - \cos\theta} \qquad \text{(III.1\_7)}$$

where i = 1, 2 for the two different trajectories that meet. While the sin is different, the cosθ is the same for both trajectories.

$$b=\frac{r\sin\theta_i}{2}\pm\frac{\sin\theta_i}{2}\sqrt{r^2+\frac{4r}{\beta(1+\cos\theta)}}$$

$$\uparrow$$

$$1,2$$

Now we get

$$\frac{db}{dr}=\frac{\sin\theta_i}{2}\pm\frac{\sin\theta_i}{2}\frac{1+\cos\theta+\frac{2}{\beta r}}{\left[\left(1+\cos\theta+\frac{2}{\beta r}\right)^2-\left(\frac{2}{\beta r}\right)^2\right]^{1/2}}$$

and we get

$$\frac{n(\vec{r},\vec{v})_1+n(\vec{r},\vec{v})_2}{n_\infty(v_b)}=\frac{1+\cos\theta+\frac{2}{\beta r}}{\left[\left(1+\cos\theta+\frac{2}{\beta r}\right)^2-\left(\frac{2}{\beta r}\right)^2\right]^{1/2}} \qquad \text{(III.1\_8)}$$

This describes the compression or focusing on the downwind side.

We see that for $\theta = \pi$ $\cos\theta = -1$ the density ratio explodes, i.e. for a cold gas we would get infinite density on the cone axis. In reality the gas is not cold, i.e. this is no problem.

The compression is equivalent to

$$\frac{|d\vec{V}|}{|d\vec{V}_\infty|}=\frac{|d\vec{r}_\infty|}{|d\vec{r}|}=|J|$$ the Jacobian Determinant of the transformation from infinity to the observation point. This can be easily seen by employing Liouville's Theorem, i.e. that the total phase space volume remains constant along trajectories.

We can now solve the same problem for a velocity distribution function:

$$N(\vec{r})=N(r,\theta)=\int f(r,\theta,\vec{v})d^3\vec{v}=\int f_\infty(\vec{v}_\infty)|J|d^3\vec{v}_\infty \qquad \text{(III.1\_9)}$$

We use a shifted Maxwellian for the neutral gas at infinity:

$$f_\infty(\vec{v}_\infty)=N_\infty\left(\frac{m}{2\pi kT}\right)^{3/2}\exp\left[-\frac{\left(\vec{V}_\infty-\vec{V}_b\right)^2 m}{2kT_o}\right]$$

(III.1_8) can be applied for each individual $\vec{v}_\infty$ with $\vec{v}_\infty=(V_\infty,\theta_\infty)$
We use a system where $\vec{V}_\infty$ is the inflow direction and in the symmetry axis (in the Figure above). Then each transformed angle $\theta' = \theta + \theta_\infty$. For example, the contribution of each (v_∞,θ) on the axis:

$$\left|J(\theta_\infty)\right|_{axis} = \frac{1+\cos\theta_\infty + \dfrac{2}{\beta r}}{\left[\left(1+\cos\theta_\infty + \dfrac{2}{\beta r}\right)^2 - \left(\dfrac{2}{\beta r}\right)^2\right]^{1/2}}$$

With this information (III.1_9) has to be integrated numerically.

However, this does not yet include the loss of neutrals due to ionization. We can use:

$$\frac{df(r,\theta,\vec{v})}{dt} = -\frac{\nu_o r_E^2}{r^2} f(r,\theta,\vec{v})$$

Homework

$$f(r,\theta,\vec{v}) = f_o(r,\theta,\vec{v}) \exp\left[-\frac{\nu_o r_E^2 \theta}{p}\right] \qquad \text{(III.1\_10)}$$

where p = b • v_∞ is the angular momentum of the incoming atom and θ the total angle subtended from infinity to the point of observation.

Finally, combining (III.1_9) and (III.1_10) with (III.1_2) we can model our measurements of the pickup ions.

Viewgraph

Data were taken September-December 1985

Viewgraph

For an ionization rate

$\gamma_{ion} = 5.5 – 6.5 \bullet 10^{-8}\ sec^{-1}$

we find $n \approx 0.07 – 0.09\ cm^{-3}$

$V_b = 19 – 25$ km/s

Viewgraph

T = 9000 – 15000 K

Viewgraph

The pitch-angle scattering, which produces our nice pick-up distribution leads also to spatial diffusion. This makes the focusing cone appear wider than it is, so we had to correct T downward and V_b upward.

Why only so few points? The method does not always work! If B is radial, i.e. B| | v_{sw}, the pickup is not efficient, and the flux is not the regular value.

Viewgraph

In this case there is no V x B electric field. The ions are moved only by scattering!

Much better and more continuous data are available now from ACE. They will lead to a better characterization of the interstellar gas parameters from pickup ion measurements.

Meanwhile also H, O, N, and Ne pickup ions have been observed, and the pickup method becomes widely used to probe the local interstellar medium.

Viewgraph

H density: $\eta_H \approx 0.1\ cm^{-3}$

In addition, direct neutral gas measurements have been made with Ulysses for He. This allows a more direct observation of the velocity distribution of the interstellar gas.

Viewgraph

In the pickup ion distribution most of this information gets lost. However, just recently we have found evidence in the data of our SOHO CELIAS instrument that the original neutral gas velocity leaves its imprint in the pickup ion distribution. On the upwind side of the interstellar flow the cut-off energy is higher than $4 \cdot E_{sw}$.

Viewgraph

Here the gas velocity and the solar wind velocity add and thus increase the size of the distribution in velocity space. Therefore, the cut-off energy of the distribution is higher.

Viewgraph

III.3 Size of the Heliosphere

Although we see neutral gas far into solar system and it loads the solar wind with additional mass after ionization (and thus slows down the wind at large distances), the wind is finally stopped by the interstellar plasma. Because we do not know well enough the interstellar plasma (it does not come into the heliosphere), we do not know the size of the heliosphere yet.

A few educated guesses are possible. Assume ram pressure balance:

$$m_p\, n_{sw}(r)\, v_{sw}^2 = m_H\, n_{plasma}\, V_{ISM}^2 \qquad \text{(III.2\_1)}$$

Homework

The value may be modified by adding an equally unknown magnetic field pressure and cosmic ray pressure. The values are easily off by factors of 2.

Although S/C are on their way out, not even the first boundary, the termination

Viewgraph

shock, where the solar wind goes subsonic, has been reached yet. The distance is still anybody's guess.

Viewgraph

What is clear though is that we are currently inside a very low-density bubble.

Viewgraph

In ≈50,000 years the neutral density of our environment may go up to several hundred or even 1000 cm^{-3}. Then our heliosphere may look completely different.