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A study on the phase-space resolution for the Solar Wind Plasma Experiment on-board Solar Orbiter

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Abstract. The Solar Orbiter mission will be dedicated to study the solar surface, the corona and the solar wind by means of remote sensing and in-situ measurements, respectively. To follow the growth phase of plasma's instabilities, at 0.21 AU, closest approach to the Sun, the full 3-D particle velocity distribution should be sampled as fast as a few tens of msec. This implies some restrictions on the maximum phase space resolution taking into account the limited allowed bit-rate for data transmission. In this paper we evaluate consequences of this limitation for solar wind distributions with different parameters.

Key words. plasma instrumentation – phase-space resolution

1. Introduction

Solar Orbiter will explore the inner regions of the solar system providing us with new insights in the plasma kinetic processes that act in the Sun's atmosphere and in the extended corona. It is fundamental to study the kinetics of the solar wind to fully understand the mechanism acting within the plasma's micro scale and to explain the role of microinstabilities generated by non-Maxwellian characteristics and anisotropies in phase-space of the velocity distribution function. It would be extremely important to study these microinstabilities during their growth phase. As they have a typical scale length of the order of the proton Larmor radius at 0.21 AU, we end with a typical time of a few tens of msec, that is the time taken by the s/c to go across such a typical length. This means that we should be able to sample the whole 3-D velocity distribution function as fast as a few tens of msec. As one needs to follow the instability for about 100 gyroperiods, typical time duration of the growth phase, and taking into account the allowed bit rate of 5 kb/s, it follows that the maximum pos-

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sible resolution would be 10 energies, 10 azimuths and 10 polar angles (see Assessment Study Report 2000).

In this work we show that this phase-space resolution is generally not sufficient to fully resolve the major ions' distribution and to compute correctly its moments.

2. Modeling the distribution function

Observations show that the major ions' solar wind distribution can be represented by a bi-Maxwellian, defined in the following way:

$$f = n\left(\frac{m}{2\pi kT_\perp}\right)\left(\frac{m}{2\pi kT_\parallel}\right)^{1/2} exp\left\{-\frac{m}{2kT_\perp}\right.$$

$$\left.\left[(v_y - V_y)^2 + (v_z - V_z)^2\right] - \frac{m}{2kT_\parallel}(v_x - V_x)^2\right\}$$

where m is the proton mass, k is the Boltzmann's constant and $V_{x,y,z}$ are the plasma flow velocity components. The variables of such distribution are the following: the number density, n; the parallel and perpendicular components of the temperature, $T_\parallel$ and $T_\perp$, with respect to the magnetic field's direction; the particle velocity components, v_x,v_y,v_z. We assume that the wind flow is parallel to the x axis.

To compute the parameters of the distribution, we first extrapolated the proton parameters to 0.21 AU, closest approach to the Sun for Solar Orbiter, using the radial trends evaluated from Helios 2 observations. We chose day 107th (Marsch et al. 1982; Marsch 1991), when the s/c was at the perihelion (0.291 AU) and the solar wind parameters were: 781 km/s for the proton velocity, 28.3 cm^{-3} for the proton number density, 48.8 eV and 83.4 eV for the parallel and perpendicular temperatures respectively.

Using the radial trends ($\beta_\parallel$=0.72 and $\beta_\perp$=1.12) and adopting r^{-2} for the density radial dependence, we obtained the proton parameters: n$_p$=54.3 cm^{-3}, T$_{\parallel p}$=61.7 eV and T$_{\perp p}$=120 eV. Moreover, we decided to study a fast wind with a velocity of 800 km/s (very similar to the one detected by Helios 2 on day 107th). We got the following alpha particle parameters (Marsch 1991): n$_\alpha$=0.05 n$_p$, T$_{\alpha\parallel}$=2 T$_{p\parallel}$, T$_{\alpha\perp}$=2 T$_{p\perp}$.

3. Computing the moments of the distribution

Given a distribution function *f*, one can define the moment of order n of such distribution:

$$M_n \equiv \int f(\mathbf{v})\mathbf{v}^n d^3$$

One can evaluate:

- the number density: $N = \int f(\mathbf{v})d^3v$,
- the number flux density vector: $N\mathbf{V} = \int f(\mathbf{v})\mathbf{v}d^3v$ (from which one can compute the velocity dividing by N),
- the moment flux density tensor: $\Pi = m\int f(\mathbf{v})\mathbf{v}\mathbf{v}d^3v$ (from which one can obtain the pressure tensor, $P = \Pi - \rho\mathbf{V}\ \mathbf{V}$ and consequently the temperature tensor ($P \equiv NkT$)),
- the energy flux density vector: $\mathbf{Q} = \frac{m}{2}\int f(\mathbf{v})v^2\mathbf{v}d^3v$ (from which one can obtain the heat flux vector, $\mathbf{H} = \mathbf{Q} - \mathbf{V}P - \frac{1}{2}\mathbf{V}Tr(P)$).

These quantities can be written by means of the counts registered by the instrument, defined as: $C = \int\int\int Svfd^3v$ where S is the effective cross-section and d^3v = v^{2}cos θ dθ dϕ dv, θ is the polar angle and ϕ is the azimuthal angle. As the incidence is perpendicular, $\theta \sim 0$, so $cos\theta \sim 1$. Dealing with discrete quantities, one can rewrite the preceding as: $C_{ijk} = f_{ijk}\,S\,v^3\Delta v_i\Delta\phi_j\,\Delta\theta_k$ or in a more compact way as $C_{ijk} = f_{ijk}\,G\,v^4$ where the geometric factor, $G = S\ cos\theta\ \Delta\phi\,\Delta\theta\Delta v/v$ has been introduced. Therefore, the distribution function can be expressed as: $f_{ijk} = C_{ijk}/G\,v^4$ (for further reading see Paschmann et al. 1998). As an example, we will obtain the number density expression. Coming back to the definition and substituting the preceding expression for *f*, one obtains: $N =$

Resolution				Moments				
n^o ϕ steps	n^o θ steps	n^o E steps	total n^o of elements	n$_c$/n$_i$	V$_c$/V$_i$	T$_{\parallel c}$/T$_{\parallel i}$	T$_{\perp c}$/T$_{\perp i}$	T$_{tot-c}$/T$_{tot-i}$
10	10	10	1000	0.48	0.91	0.78	0.86 0.95	0.87
18	18	10	3240	0.48	0.91	0.78	0.86 0.95	0.85
10	10	32	3200	0.98	1.0	0.89	1.0 1.1	1.0

Table 1. Normalized moments computed with respect to the input values (c=computed, i=input) as a function of the number of energy steps, of polar and azimuthal angles.

$\int\int\int \frac{C}{G\, v^4}\, v^2\, cos\theta\, d\theta\, d\phi\, dv$ that becomes: $N = \frac{\Delta\theta\,\Delta\phi}{G} \sum_{v_i} \frac{\Delta v_i}{<v_i^2>} \sum_{\phi_j} \sum_{\theta_k} cos\theta_k\, C_{ijk}$ where $\Delta\theta$ and $\Delta\phi$ are the amplitudes of the polar and azimuthal sectors, respectively, while Δv_i is the amplitude of the energy channel. The average over v_i^2 is an average over the four adjacent energy sub-channels that constitute an energy channel while $cos\theta_k$ is computed using the central angle of the polar sector. Expressions for the other moments are obtained in a similar way.

We assume a field of view varying from -45^o to +45^o both in azimuthal and polar direction (D'Amicis et al. 2001). The energy variation law is assumed exponential and the energy limits vary from 15000 eV to 10 eV in order to cover the entire energy distribution.

We computed the principal moments as a function of some possible combinations of the number of azimuths, polar angles and energy steps, i.e. varying $\Delta\theta$, $\Delta\phi$ and ΔE, starting from the resolution suggested in the Assessment Study Report (2000) of 9^o and 10 energy steps, down to 5^o and 32 energy steps (Helios resolution). Our model distribution is characterized by a proton bi-Maxwellian distribution, whose parameters have already been computed in the preceding section.

In Table 1, we show only three cases that, in our opinion, are the most representative. These results show that the lowest resolution, the one suggested in the Assessment Study Report, causes large uncertainties in the computation of the principal moments. The other two resolutions, even if they have almost the same number of total elements, reproduce different results. Actually, the (18×18×10) combination has a high angular resolution and a low energy resolution while the (10×10×32) combination has a high energy resolution and a low angular resolution. We notice that the number of energy steps is the most important parameter. Actually, n, V and $T_{\parallel}$ are more sensitive to this parameter while they do not show any sensitiveness to the angular resolution when the energy resolution is kept constant.

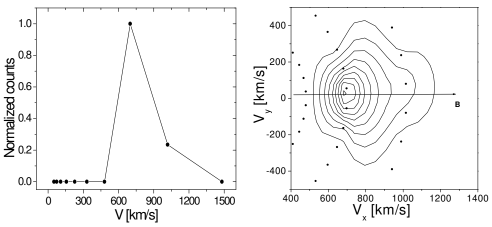

Fig. 1. Counts vs. velocity (left panel) and contour plots integrated over θ (right panel) computed with a phase-space resolution of 10 ϕ, 10 θ and 10 E. The first contours correspond to 10 % of the maximum phase-space density.

4. Sampling the distribution function

As a second step, we intend to study how the instrument samples a distribution function, obtained as the sum of two bi-Maxwellians, one for protons and the other one for alpha particles, varying the number of energy steps, polar and azimuthal angles.

We made simulations for different phase-space resolution but we noticed that the alpha peak emerges when we use 24 energy steps, at least. In this section, we present only the results for the lowest resolution and the (10×10×32) resolution. Fig. 1, which refers to the lowest resolution, shows the counts as a function of velocity (left panel) and the contour plots computed integrating over the polar angle (right panel). It is clear that this resolution is not sufficient to fully resolve the distributions of the major ions since the alpha particle peak does not show up.
In Fig. 2, the same fast wind is resolved using a higher resolution, i. e. 10 ϕ, 10 θ and 32 E and the alpha peak is now clearly identifiable.

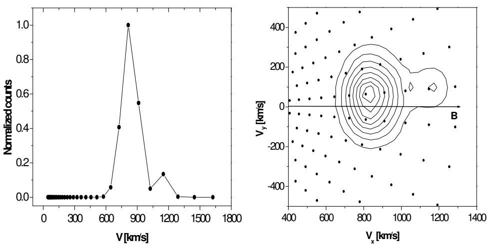

Fig. 2. Counts vs. velocity (left panel) and contour plots integrated over θ (right panel) computed with a phase-space resolution of 10 ϕ, 10 θ and 32 E. The first contours correspond to 10 % of the maximum phase-space density.

5. Conclusions

We computed the moments of a proton bi-Maxwellian distribution as a function of the resolution used for energy, polar and azimuthal angles. The resolution firstly suggested in the Assessment Study Report seems to be inadequate. If we compare two resolutions with almost the same total number of elements, we find very different results. Actually, the number of energy steps seems to be the most important parameter to which the computation of n, V and $T_{\|}$ is very sensitive. Taking into account also the alpha particles, we find that the sampling of the distribution functions with the lowest resolution does not show any evidence for the alpha particles peak. By increasing the energy steps and leaving unchanged the angular resolution, we observe that the alpha peak is clearly identifiable.
To better resolve the major ions' distribution, we propose a higher phase-space resolution than the one firstly suggested in the Assessment Study Report. From our simulations, it emerges that an angular resolution of 10 ϕ and 10 θ is sufficient but, a minimum of, at least, 24 energy steps is needed.

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