PICK-UP ION MEASUREMENTS IN THE HELIOSPHERE – A REVIEW

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Abstract. Measurements of the composition and spatial distribution of pick-up ions inside the heliosphere are reviewed. The first interstellar $^4He^+$ pick-up ions were detected with the SULEICA instrument on the AMPTE spacecraft near Earth's orbit. Most data on pick-up ions were taken in the solar-wind and suprathermal energy range of SWICS on Ulysses while the spacecraft cruised from 1.4 to 5.4 AU and explored the high-latitude heliosphere and solar wind from the ecliptic to ±80° heliolatitude. This includes the discovery of H^+, $^4He^{++}$, $^3He^+$, N^+, O^+, and Ne^+ pick-up ions that originate from the interstellar neutral gas penetrating the heliosphere. From their fluxes properties of the interaction region between the heliosphere and the Local Interstellar Cloud such as the limits on filtration and the strength of the interstellar magnetic field have been revealed. Detailed analysis of the velocity distributions of pick-up ions led to 1) the discovery of a new distinct source, the so-called Inner Source, consisting of atoms released from interstellar and interplanetary dust inside the heliosphere, 2) the determination of pick-up ion transport parameters such as the long mean free path for pitch-angle scattering of order 1 AU, and 3) detailed knowledge on the very preferential injection and acceleration of pick-up ions during interplanetary energetic particle events such as Co-rotating Interaction Regions and Coronal Mass Ejections. SWICS measurements have fully confirmed the theory of Fisk, Koslovsky, and Ramaty that pick-up ions derived from the interstellar gas are the dominant source of the Anomalous Cosmic Rays; they are pre-accelerated inside the heliosphere and re-accelerated at the solar-wind Termination Shock according to Pesses, Eichler, and Jokipii. The data indicate that the Inner Source of pick-up ions is largely responsible for the occurence of C^+ in the Anomalous Cosmic Rays. The abundances of recently discovered Inner-Source Mg^+ and Si^+ are solar-wind like and consistent with their abundances in the energetic particles associated with Co-rotating Interaction Regions.

Knowledge on the injection and acceleration processes in Co-rotating Interaction Regions is applied to discuss the current observational evidence for the Interplanetary Focusing Cone of the interstellar neutral gas due to the Sun's gravitational force. The 25–150 keV/amu suprathermal $^4He^+$ pick-up ion fluxes measured by CELIAS/STOF on board SOHO over 360° of ecliptic longitude represent a 'local' ionization and acceleration of interstellar atoms at 1 AU or smaller heliocentric distances. Completing the first limited data set of SULEICA/AMPTE on $^4He^+$ pick-up ions they indicate a density enhancement in the Interplanetary Focusing Cone which is confirmed by recent SWICS/ACE data.

Clear evidence for signatures in ecliptic longitude are found in the data on energetic neutral H fluxes observed with the CELIAS/HSTOF sensor on board SOHO. These fluxes are enhanced in the upstream and downstream directions of the interstellar wind. Detection of energetic H atoms, which propagate unaffected by the Heliospheric Magnetic Field, provided for the first time a diagnostic tool for observations near Earth to analyze the structure in ecliptic longitude of the interface region between the heliosphere and the Local Interstellar Cloud.

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1. Introduction

In the Local Interstellar Cloud (LIC) matter exists in the form of atoms, ions and grains or dust. Only atoms and very low-charged grains can enter the heliosphere. For H, O, and Ne there is a reduction in the density of atoms reaching the solar-wind Termination Shock (TS) compared to their abundance in the LIC. In the 100–200 AU wide so-called filtration region beyond the heliopause they suffer loss by charge-exchange with the slower moving interstellar protons as pointed out by Baranov and Malama (1995). The distribution and density of the interstellar H atoms were first measured by Bertaux *et al.* (1985) with a hydrogen absorption cell measuring the Lyman-α backscattering on the PROGNOZ 5 and 6 spacecraft. It was discovered that the interstellar neutral H gas flows with a velocity of $\sim$ 20 km s^{-1} relative to the heliosphere. Along its downstream axis at $\sim 74°$ ecliptic longitude the interstellar gas forms a region of pronounced density increase due to the gravitational force of the Sun, the so-called Interplanetary Focusing Cone.

In contrast to H, O, and N atoms, He and Ne are not effected while passing the filtration region. They penetrate deepest into the heliosphere because of their low ionization efficiency by solar ultraviolet (UV) light compared to e.g. H atoms (Rucinski *et al.*, 1996). Therefore, neutral He remains the dominant component of the interstellar wind close to Earth's orbit. Indeed, $^4He^+$ ions were first observed as interstellar pick-up ions using the SULEICA instrument on the AMPTE spacecraft at 1 AU (Figure 1, *upper left*, Möbius *et al.*, 1985). In analogy to the behavior of the H interstellar gas the He atoms form an Interplanetary Focusing Cone. Its width in ecliptic longitude at 1 AU is $\sim 20°$ as determined by optical observations (Lallement *et al.*, 1990). Using the limited set of AMPTE data in the range of ecliptic longitudes near this Focusing Cone, Möbius *et al.* (1995) estimated the temperature of neutral He in the LIC to be of order 9000–15000 K. Recent detailed measurements with SWICS on ACE (Gloeckler *et al.*, 1998) of the pick-up $^4He^+$ flux in 1998 as a function of ecliptic longitude revealed the temperature of interstellar He to be $\sim$ 6000 K (Gloeckler, 2000, personal communication).

Most of the discoveries on the composition and spatial distribution of interstellar pick-up ions in the heliosphere originate from measurements with the Solar Wind Ion Composition Spectrometer (SWICS, Gloeckler *et al.*, 1992) on board the Ulysses spacecraft. With SWICS, a carbon-foil time-of-flight spectrometer capable to resolve the elements in the mass range from 1 to 60 amu, the first interstellar H^+ was detected (Gloeckler *et al.*, 1993) as well as the first interstellar O^+, N^+, and Ne^+ (Geiss *et al.*, 1994a) pick-up ions. Later, Geiss *et al.* (1995) discovered pick-up C^+ ions as constituent of a distinct particle population in the heliosphere, the so-called distributed Inner Source (Geiss *et al.*, 1996). These Inner-Source C^+ particles are seed ions of C^+ observed in the Anomalous Cosmic Rays (ACRs).

In particular, the detailed analysis of the velocity distribution functions of the pick-up ion species with SWICS/Ulysses at different heliolatitudes, solar wind conditions, and heliocentric distances gave insight into the interstellar gas dynamics. This is important to e.g. correctly derive the composition of the LIC which is summarized in a recent review (Gloeckler and Geiss, 1998).

The SWICS data are complemented by data covering 360° ecliptic longitude from the (Highly) Suprathermal Time-of-Flight sensors (H)STOF of the Charge, Element, and Isotope Analysis System (CELIAS, Hovestadt *et al.*, 1995) on board the SOHO spacecraft at 1 AU. We briefly review the longitudinal signatures of suprathermal $^4He^+$ pick-up ions detected by STOF. They represent a rather ‘local’ $^4He^+$ particle population injected and accelerated at or inside 1 AU. The energetic H atom fluxes observed with HSTOF originate from the heliospheric interface region and reflect its longitudinal structure.

Both, SWICS/Ulysses at first and then CELIAS/STOF data, made evident that pick-up ions are extremely selectively accelerated in Co-rotating Interaction Region (CIR) and interplanetary Coronal Mass Ejection (CME) events. Re-accelerated at the TS (Pesses *et al.*, 1981), they dominate the composition of the ACRs (Fisk *et al.*, 1974).

2. Pick-up Ions Observed With SWICS/Ulysses at Varying Heliocentric Distances and Heliolatitudes

SWICS/Ulysses data were first taken while the spacecraft cruised from 1.4 AU to 4.5 AU; then it by-passed Jupiter to leave the ecliptic plane and – after a first heliolatitudinal descent – fly over the southern solar pole. Therefore, Ulysses explored heliospheric regions of varying solar UV flux, interstellar neutral gas flux, gravitational force, Heliospheric Magnetic Field (HMF), and density of interstellar and interplanetary dust, as well as different locations relative to planetary atmospheres and comets.

2.1. Interstellar pick-up ions

At heliocentric distances between 1.4 AU and 4.5 AU the ratio of H^+ to $^4He^+$ interstellar pick-up ion fluxes steadily increased. This observation proved that He penetrates deeper into the heliosphere than H because of its smaller loss rate due to the ionization by solar UV. From the best fit to the data (Figure 1, *lower right*) the ionization loss rate of H was found to be 5.5×10^{-7} s^{-1} assuming the ratio of radiation to gravitational force of the Sun is 1, the H/He abundance ratio at the TS is 7.5, and the loss rate for He is 0.55×10^{-7} s^{-1} (Gloeckler, 1996). These ionization rates are in good agreement with average values obtained independently by Rucinski *et al.* (1996).

To determine correctly interstellar H and He pick-up ion fluxes they must be distinguished from solar wind ions or pick-up ions originating from the solar system. He pick-up ions are predominantly singly charged, whereas solar wind He^+ is seldom observed (see Gloeckler, 1999, and references therein). However, Inner-

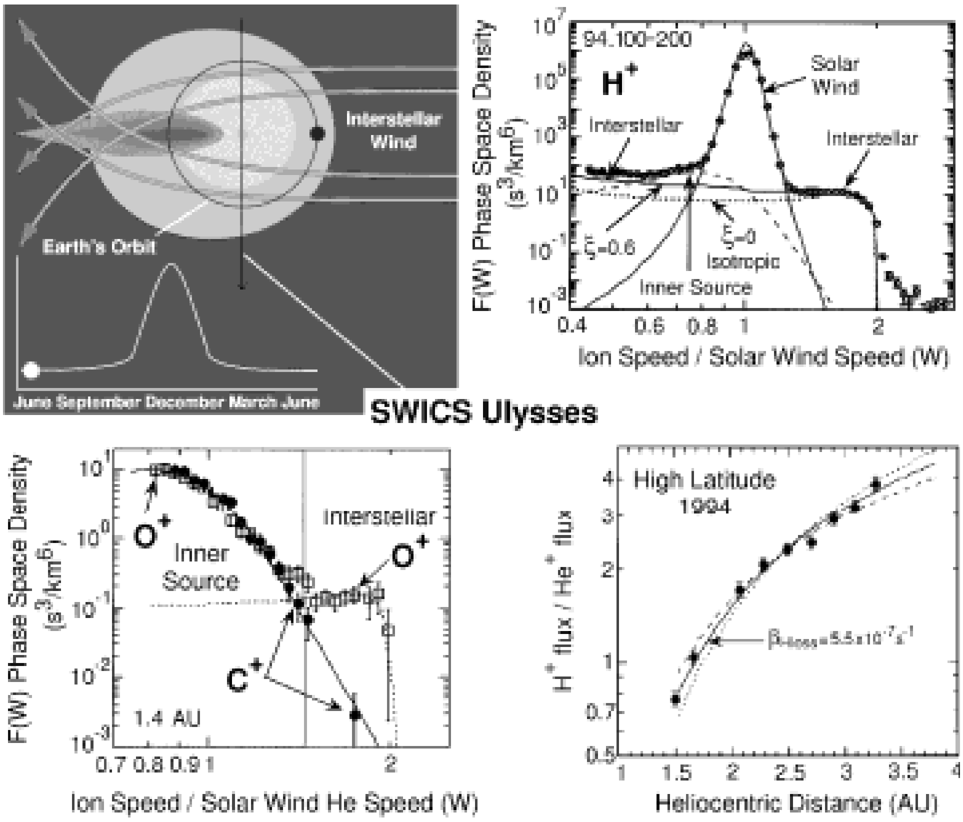

Figure 1. Schematic representation of the interstellar gas distribution in the inner and middle heliosphere (*upper left*, adapted from Möbius *et al.*, 1999a). Typical gas particle trajectories and the density enhancement in the Interplanetary Focusing Cone are shown. The approximate trajectories of the AMPTE, SOHO, and ACE spacecraft near Earth are overlayed (for data at 1 AU see Figure 3) as well as the direction of the Ulysses orbit projected onto the ecliptic plane. With SWICS on Ulysses (data from Gloeckler and Geiss, 1998) many details of the velocity distribution of interstellar pick-up ions have been revealed which made it possible to distinguish them from solar wind ions (*upper right*) and from Inner-Source pick-up ions (*bottom left*). The parameter W denotes the ratio between the ion speed and the solar wind bulk speed. The degree of anisotropy, ξ, is related to the probability of pitch-angle scattering with respect to the HMF and defined in terms of the ratio, ρ, of the density in the $< 90^\circ$ ($W < 1$) to that in the $> 90^\circ$ pitch-angle ($W > 1$) hemisphere of phase-space, $\rho = (1 + \xi)/(1 - \xi)$. Also, the change of the ratio in the $^4He^+/H^+$ interstellar pick-up ion fluxes with heliocentric distance due to the different ionization rates has been discovered (*bottom right*).

Source pick-up ions are mainly singly charged as well, and for H the charge state argument does not hold at all to distinguish the species.

The most reliable distinction is given by the velocity distributions of the different particle species (Gloeckler *et al.*, 1997; Gloeckler and Geiss, 1998) which is outlined for the example of interstellar He: Interstellar neutral ^{4}He moves with a mean velocity of 25.3 km s^{-1} (Lallement *et al.*, 1990) into the heliosphere. On its way to 1 AU it is accelerated to about 46 km s^{-1} by the gravitational force of the Sun. When they are ionized by the solar UV radiation the $^4He^+$ ions immediately are picked up by the electromagnetic field of the solar wind which moves faster with bulk velocities on the order of 400–800 km s^{-1}, and hence are rapidly convected in the anti-sunward direction. The pick-up ion velocity distributions strongly depend on the HMF. In the ecliptic plane, at heliocentric distances of more than a few AU, the HMF is nearly perpendicular to the solar wind flow. Thus, the pick-up ions move on Larmor orbits around the HMF and are subsequently pitch-angle scattered into shell distributions in velocity space. The center of this shell coincides with the solar wind bulk velocity, and its radius approximately equals the solar wind bulk speed depending on the initial velocity distribution of the neutral atoms. Such distributions have been observed with SWICS/Ulysses at low latitudes. It was demonstrated that solar wind and pick-up H^+ can well be distinguished by their velocity distributions (Figure 1, *upper right*).

At higher latitudes and closer to the Sun the HMF is nearly parallel to the solar wind flow. Therefore, pitch-angle scattering through 90° is required to fill the full shell in velocity space. The asymmetries observed in the distribution functions depending on the position of the Ulysses spacecraft in the heliosphere implies that pitch-angle scattering through 90° is very inefficient (Gloeckler and Geiss, 1998). The mean free path with respect to pitch-angle scattering was determined to be of order 1 AU (Gloeckler *et al.*, 1995).

With data from the SOHO/CELIAS Charge Time-of-Flight (CTOF) sensor, Möbius *et al.* (1999b) recently demonstrated that the pick-up ion velocity distribution depends on that of the interstellar neutral gas. On the downwind (upwind) side, the so-called pick-up ion cut-off speed roughly equals the sum (difference) of the solar wind speed and the interstellar gas speed. This effect is naturally more pronounced in the slow solar wind. It provides a valuable tool to determine the interstellar gas flow including gravitational acceleration by the Sun. Thus, it complements direct neutral gas measurements.

2.2. INNER SOURCE PICK-UP IONS

In Figure 1 (*upper right*) one sees a small deviation from the distributions expected from solar wind ions and interstellar pick-up ions. It was discovered by Geiss *et al.* (1995) that this is a signature of another species (see also Gruntman, 1996; Schwadron *et al.*, 2000), the Inner-Source pick-up ions. The Inner Source is pronounced inside 1 AU and consists of atoms adsorbed in interstellar and interplanetary dust inside the heliosphere. The velocity distributions of their pick-up ions are peaked at the solar wind bulk velocity but much wider than the solar wind distribution (Figure 1, *lower left*). Although the details of these distributions are still under debate, they may be explained by the nearly radial HMF inside 1 AU. Adiabatic cooling in the expanding solar wind is mainly effective perpendicular to the magnetic field and leads to the observed distributions.

In our terminology, Inner Source pick-up ions are different from pick-up ions as they were first observed from the Moon with AMPTE/SULEICA (Hilchenbach *et al.*, 1991), from Venus with CELIAS/CTOF (Grünwaldt *et al.*, 1997), and from the comet Hyakutake with SWICS/Ulysses (Gloeckler *et al.*, 2000a). These planetary and cometary pick-up ions are a neglegible component in the heliosphere. Geiss *et al.* (1994b) and Ogilvie *et al.* (1995) proved, e.g. that O^+ measured by SWICS in the aphelion region of the Ulysses trajectory is not of Jovian origin. Inner-Source pick-up ion fluxes, however, need to be considered when determining interstellar pick-up ion fluxes.

The main constituents of the Inner Source are C and O with approximately equal abundances (Gloeckler and Geiss, 1998). Heliospheric C^+ pick-up ions are predominantly Inner-Source particles. The upper limit for the interstellar C^+/O^+ abundance ratio in the heliosphere is 0.05 as C is mostly ionized in the LIC (Frisch, 1998) and thus mainly excluded from the heliosphere.

Inner-Source particles are an important seed population for the ACRs besides the H, He, N, O, and Ne component originating from the interstellar gas. This was first discussed by Geiss *et al.* (1995) for C^+ and by Gloeckler and Geiss (1998) for Inner-Source Ne^+. Inner-Source Mg^+ and Si^+ pick-up ions were recently discovered with SWICS/Ulysses at ~ 1.5 AU and at low to middle ($< \pm 60^\circ$) heliolatitudes (Gloeckler *et al.*, 2000b). Their abundances agree with the solar-wind like composition of the particles accelerated in CIRs (Mason and Sanderson, 1999; Mason *et al.*, 1999). Gloeckler *et al.* (2000b) suggest that a large fraction of the Inner Source consists of adsorbed solar-wind particles. In this context, the ACR composition is discussed by Gloeckler *et al.* (2000c). The newest data on ACR abundances including the minor components C, Mg, Si, S, and Fe are reported by Cummings *et al.* (1999).

2.3. Density, composition, and magnetic field of the local interstellar cloud

All these findings and existing models were considered when creating Table I on the abundances of H, He, N, O, and Ne at the TS and in the LIC (Gloeckler, 1996; Gloeckler *et al.*, 1997; Gloeckler and Geiss, 1998). In particular, Table I reflects the fact that the loss for O in the 100–200 AU wide filtration region beyond the heliopause is less than for H. It was first estimated by Geiss *et al.* (1994c) and later confirmed by numerical model calculations (Izmodenov *et al.*, 1999ab) that about 40% of H in the LIC remains excluded from the heliosphere, whereas up to 90% of LIC O penetrates into the solar system. Note, that the sensitivity of the SWICS/Ulysses instrument was sufficient to determine the isotopic abundance ratio $^3He/^4He$ (see Table I, Gloeckler and Geiss, 1996) which is very important for cosmology. The $^3He/^4He$ abundance ratio is altered in the solar system by nuclear burning so that it is difficult to find its value for the early solar nebula measuring abundances in samples originating in the solar system.

TABLE I

Densities of atoms at the TS ($\sim$ 85–110 AU) and densities of atoms and ions in the LIC of elements and isotopes measured as pick-up ions with SWICS on Ulysses (from Gloeckler and Geiss, 1998)

Isotope	Termination Shock		Local Interstellar Cloud				Solar
	Ratio	Density	Density* (10^{-5} cm^{-3})			Ratio	system
	(10^{-3})	(10^{-5} cm^{-3})	Atoms	Ions	Total	(10^{-3})	ratio (10^{-3})
^{1}H	7500	11500 ± 2500	20000	4300	24300	10000	10000
^{3}He	0.248	0.38 ± 0.1	0.38	0.22	0.6	0.25	–
^{4}He	1000	1530 ± 180	1530	900	2430	1000	1000
^{14}N	0.6	0.92 ± 0.28	1.0	0.22	1.2	0.51	1.12
^{16}O	5.1	7.8 ± 1.4	9.5	2.1	12	4.8	8.51
^{20}Ne	0.75	1.15 ± 0.25	1.15	0.67	1.8	0.75	1.23

* Assuming the same ionization fraction for N and O as measured for H (0.18) and for Ne the same as for He (0.37).

Gloeckler *et al.* (1997) also estimated the magnetic field strength in the LIC by magnetohydrodynamical pressure balance arguments and based on the following assumptions: 1) There is a bow shock at the outer boundary of the filtration region, 2) the magnetic field orientation is nearly parallel to the shock surface as observed by Frisch (1995), 3) the TS is, according to observations of ACRs from the Voyager 1 and 2 spacecraft, at least at a heliocentric distance of 80 AU which constrains the solar-wind pressure at the heliopause, 4) the density of the LIC is 0.2 cm^{-3} (Table I), and 5) H in the LIC flows with a mean speed of 26 km s^{-1} relative to the heliosphere. They concluded that the most probable value for the LIC magnetic field strength is in the range between 1.3 and 2 μG and must be less than 4.3 μG. This value derived by pick-up ion measurements agrees remarkably well with the observed value of (1.4 ± 0.15) μG (Frisch, 1995).

2.4. Preferential injection and acceleration of pick-up ions

Because of their very non-thermal velocity distribution the pick-up ions are extremely favored for injection into the acceleration process in interplanetary energetic particle events such as CIRs (Balogh *et al.*, 1999). This is the reason why interstellar particles dominate in the ACRs (Fisk *et al.*, 1974) although their source fluxes in the inner and middle heliosphere are by far less than the solar wind flux.

The shocks or the turbulence associated with CIRs create, mainly in the downstream region, strong suprathermal tails on top of the typical shell distribution observed in the quiet wind. In these suprathermal tails at ion speeds beyond twice the solar wind bulk speed pick-up He^{+} observed at 4.5 AU (Figure 2) is more abundant by up to a factor 10 than solar wind He^{++} although the source density is at least three orders of magnitude less. The suprathermal tails for the different species

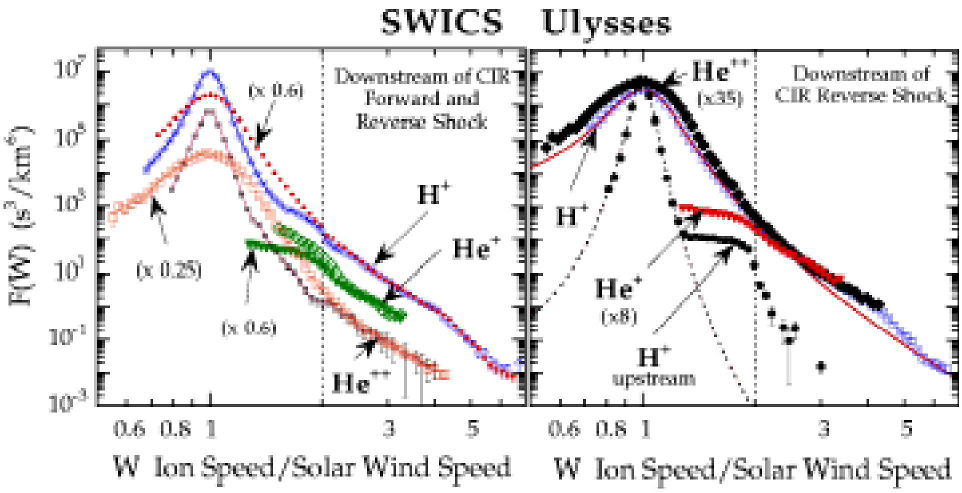

Figure 2. Left: Distribution functions of H^+, He^+ and He^{++} downstream of the forward shock (*open circles, triangles and small squares respectively*) and downstream of the reverse shock (*filled circles, diamonds and large squares respectively*) of the late December 1992 CIR. *Right*: Velocity distributions of H^+ (*squares*), He^+ (*triangles*) and He^{++} (*filled diamonds*) in the region downstream of the reverse shock. We note that (a) the tails (above $W \approx 2.5$) of all three ion species have the same shape in the downstream region of the shock, and that the shape is not a simple power law as predicted by standard shock acceleration models, (b) the He^+/He^{++} ratio in the tail is ~ 4.4, and (c) the $H^+/(He^+ + He^{++})$ ratio in the tail is about 6.5 (from Gloeckler, 1999, see also Geiss *et al.*, 1994c, and Gloeckler *et al.*, 1994).

are not power law distributions as predicted from diffusive acceleration models (Fisk and Lee, 1980). However, they all have similar shapes which implies that the pre-acceleration process creating the tails is mainly selective for the velocity but not the charge-to-mass ratio of the particles. Thus, the relative abundances of the suprathermal particles depend on their seed particle velocity distributions.

Schwadron *et al.* (1996) have found that the suprathermal particle fluxes are strongly correlated with high magnetic field turbulence levels in the compressed solar wind within CIRs. For energies below 100 keV/amu, transit time damping appears to be the dominant acceleration mechanism. Pick-up ions are strongly preferred by transit time damping because, unlike the solar wind ions, they can fulfill the necessary Landau resonance condition. This finding implies that shocks do not need to form in CIRs to cause strongly suprathermal particle distributions. However, at heliocentric distances of a few AU well developed shocks do occur fairly frequently within CIRs.

A typical injection mechanism, which prefers the pick-up ions because of the overlap of their velocity distribution with the shock propagation velocity, is shock surfing (Sagdeev, 1966). A fraction of the gyrating pick-up ions approximately co-moving with the shock find themselves trapped between the electrostatic shock potential and the upstream Lorentz force. They gain energy in the $\mathbf{v} \times \mathbf{B}$ field inside the shock layer (Kallenbach and Lee, 1999) until they reach approximately the maximum electron drift velocity inside the shock – independent of their charge-to-mass ratio.

These injection and acceleration mechanisms do not only apply for CIRs but also for CMEs. As CIRs do, CMEs preferentially accelerate pick-up ions (Bamert *et al.*, 1999; Gloeckler *et al.*, 1999). However, CMEs are more individual in their shock and plasma parameters, e.g., their shocks or waves are not always quasi-perpendicular as in the case of CIRs. This explains why the observed abundance ratio of energetic $^4He^+$ and $^4He^{++}$ associated with CMEs (Hovestadt *et al.*, 1981; 1984) strongly varies from event to event.

3. Signatures in Ecliptic Longitude of $^4He^+$ Pick-up Ion Fluxes Observed Near Earth With AMPTE/SULEICA and SOHO/CELIAS

In this section, we report on data representing the variation in ecliptic longitude of $^4He^+$ pick-up ion fluxes. Unfortunately, the data set of $^4He^+$ pick-up ions from the SULEICA instrument (Möbius *et al.*, 1995) in the range of ecliptic longitudes near the Interplanetary Focusing Cone is limited. Part of the AMPTE spacecraft's orbit goes through Earth's magnetosphere where interstellar pick-up ions cannot be observed. Therefore, we have to complete the view over 360° ecliptic longitude by SOHO/CELIAS/STOF data on $^4He^+$ pick-up ions accelerated above 25 keV/amu by a recurrent CIR event. We need to argue briefly how well these suprathermal $^4He^+$ fluxes represent the source population of interstellar pick-up ions. At the same time, this argumentation reflects some of the knowledge on transport, injection, and acceleration of pick-up ions and their spatial distribution in the heliosphere as a dominant energetic particle population.

The data from the CELIAS/STOF sensor (Figure 3; Hilchenbach *et al.*, 1999; Kallenbach and Hilchenbach, 1999) were taken on board SOHO during the years 1996–1997 near solar activity minimum. Anti-sunward directed suprathermal particle fluxes in the 25–150 keV/amu energy range of $^4He^+$ pick-up and $^4He^{++}$ solar wind ions associated with a recurrent CIR event have been measured. Complementing the data with the AMPTE/SULEICA results, two maxima of the $^4He^+/^4He^{++}$ flux ratio $f_{+,++}$ close to the upstream and downstream direction of the interstellar wind can be identified. The downstream maximum is about 20° (FWHM) wide in agreement with the optically observed width of the downstream Interplanetary Focusing Cone built up by the ^4He interstellar neutral gas (Lallement *et al.*, 1990). It appears to be shifted eastward (see also Möbius *et al.*, 1995). The upstream maximum is much wider in longitude and appears to be shifted westward but is much less pronounced – if at all significant.

Other causes than a variation of the interstellar neutral He source gas density for the signatures in $f_{+,++}$ associated with recurrent CIRs are rather unlikely. A constant source density ratio $^4He^+/^4He^{++}$ before injection for all recurrent events

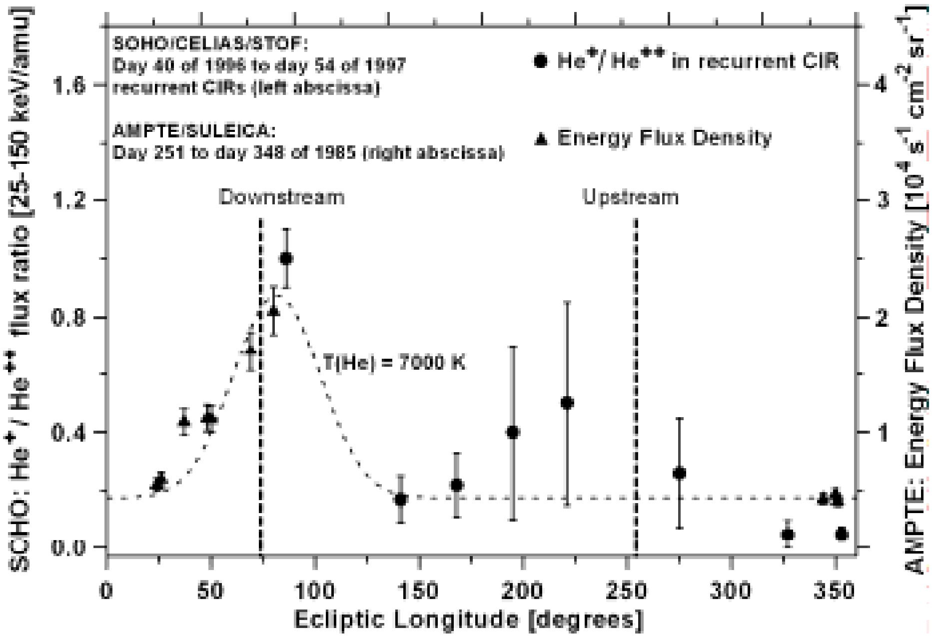

Figure 3. Variation with ecliptic longitude of the energy flux density of interstellar $^4He^+$ pick-up ions from AMPTE/SULEICA data (Möbius *et al.*, 1995), and the suprathermal $^4He^+/^4He^{++}$ abundance ratio in the energy range 25–150 keV/amu associated with recurrent CIRs from SOHO/CELIAS/STOF data (Hilchenbach *et al.*, 1999). The upstream and downstream directions of the interstellar wind are marked. For the STOF data the 6-hour intervals after onset of each recurrent event are shown which always resulted in the highest $^4He^+/^4He^{++}$ ratio during the whole event. Error bars indicate the experimental uncertainty due to statistics and instrument efficiencies. A simplified model function for the $^4He^+$ pick-up ion source distribution centered at 82° ecliptic longitude is shown for the interstellar neutral He parameters $T_\infty = 7000$ K and $V_\infty = 25.3$ km s^{-1} from Witte *et al.* (1993).

in Figure 3 can statistically almost be excluded by a χ^2 test. The ratio $r_{+,++}$ between the injection and acceleration efficiency for $^4He^+$ and $^4He^{++}$ would need to vary by a factor 5 to make the observed variation in $f_{+,++}$ likely. $f_{+,++}$ varied not more than by a factor 3 when the SOHO spacecraft passed the same CIR 3 times (Hilchenbach *et al.*, 1999) close to a 'wiggle' in the stream structure, so that we expect less variation over subsequent Carrington rotations when the same CIR passes away from such a 'wiggle'. Furthermore, the mean energy of suprathermal particles accelerated independently of their charge-to-mass ratio by transit time damping varies by a factor 5 if the normalized magnetic turbulence levels vary by a factor 3 (Schwadron *et al.*, 1996). Therefore, we do not expect a strong variation of $r_{+,++}$ even if the magnetic turbulence levels associated with CIRs (see, e.g., Horbury and Schmidt, 1999) vary considerably.

A variation in the solar wind He^{++} seed particle density is also unlikely to be the cause for the variation of $f_{+,++}$ associated with recurrent CIRs because they arise

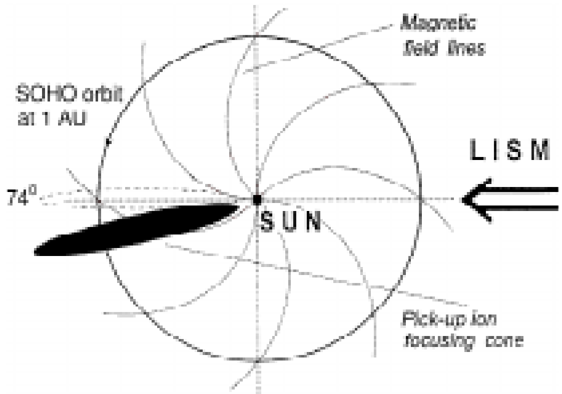

Figure 4. Schematic representation of the He^+ pick-up ion cone in the ecliptic plane reflecting the pick-up ion implantation from the Interplanetary neutral Helium Cone (see dashed configuration) which is symmetric to the Local Interstellar Medium (LISM) downwind axis (adapted from the model of Chalov and Fahr, 1999).

from co-rotating coronal configurations which are fairly stationary over several Carrington rotations.

It is emphasized here that the observation of a mean $f_{+,++}$ of 0.15 at 1 AU proves that these particles are ionized and accelerated 'locally' near 1 AU because at 4.5 AU a ratio of about 10 has been measured (Gloeckler and Geiss, 1998). The transport of suprathermal particles from 4.5 AU to 1 AU cannot alter $f_{+,++}$ by two orders of magnitude (Fisk and Lee, 1980). Only pick-up ions created further sunward within 1 AU and convected outward may contribute to some extent to the fluxes observed at the SOHO location.

We consider it most likely that the data indicate a variation of the $^4He^+$ pick-up ion flux, i.e. of the interstellar neutral He flux with ecliptic longitude. The distribution presented in Figure 3 matches a source distribution of the downstream interstellar ^4He neutral gas described by the Interplanetary Helium Cone (Chalov and Fahr, 1999). This cone has a width (FWHM in density)

$$\Phi_c = \frac{4}{3}\left(\frac{\pi m V_\infty^2}{2kT_\infty}\right)^{-\frac{1}{2}} = 2.^\circ 8\,\frac{\sqrt{T_\infty[\mathrm{K}]}}{V_\infty\ [\mathrm{km\ s^{-1}}]} \tag{1}$$

in ecliptic longitude, where m is the mass of the ^4He atom, T_∞ is the temperature, and V_∞ is the velocity of ^4He in the LIC. The observed width in the suprathermal $^4He^+/^4He^{++}$ abundance ratio would approximately match the parameters $T_\infty =$ 7000 K and $V_\infty = 25.3$ km s^{-1} by Witte *et al.* (1993) including corrections due to $^4He^+$ pick-up ions created further sunward.

In the model of Chalov and Fahr (1999) the most obvious deviation in the interstellar $^4He^+$ pick-up ion distribution from the Interplanetary Helium Cone is a shift of the intensity maximum in ecliptic longitude (Figure 4). They explain this phenomenon based on the idea that the $^4He^+$ pick-up ions do not strictly co-move with a solar wind parcel as a consequence of the diffusion and convection process in the solar wind plasma. When judged from the solar wind reference frame, freshly created pick-up ions start with negative pitch-angle cosine $\mu_0 < 0$. If the process of pitch-angle scattering is not effective, these ions lag behind the radially expanding solar wind. Therefore, the HMF, which co-rotates with the Sun, carries them into the eastward direction in ecliptic longitude (see also Möbius *et al.*, 1995). The magnitude of the shift is determined by the HMF configuration and by the value of the mean free path of $^4He^+$ pick-up ions, i.e., the level of solar wind turbulence (Horbury and Schmidt, 1999). If diffusion is inefficient the $^4He^+$ moves with a solar wind parcel. If the normalized Alfvénic turbulence level, $\delta =< \delta B^2 > / < B^2 >$, is about 0.01 the mean free path $\Lambda_\parallel$ along the HMF is 0.2 AU, and the expected shift of the $^4He^+$ cone is 5°; for $\delta = 0.002$ we have $\Lambda_\parallel = 1$ AU, and the shift can be up to 10° at 1 AU.

There are now more direct measurements with ACE/SWICS during 1998 on the interstellar $^4He^+$ pick-up ion fluxes at 1 AU near the Interplanetary Focusing Cone (Gloeckler, 2000, personal communication). However, no shift of the flux maximum by more than 1–2° from the nominal downstream direction of the interstellar wind is observed. With ACE/SWICS mainly the $^4He^+$ pick-up ions in the tail of the velocity distribution above the solar wind bulk speed contribute to the data analysis. These ions are not expected to show the same shift as the suprathermal particles observed with CELIAS/STOF. The latter are injected into CIRs mainly from the tail of the velocity distribution co-moving with the CIR forward or reverse wave (or shock). These are the typical particles lagging behind the solar wind flow as described above. Another reason for the observation of smaller shifts in the ACE/SWICS data could be that in 1998 the solar cycle approaches its maximum. Then, turbulence levels in the solar wind are higher and reduce the mean free path for pitch-angle scattering of the pick-up ions. Möbius *et al.* (1995) also discussed the effect of the data accumulation time and the spacecraft's co-movement with Earth on the value of the observed longitudinal shift.

4. Energetic Hydrogen Atoms From the Heliospheric Interface Observed Near Earth by SOHO/CELIAS

A 360° panoramic view to the heliosphere was recorded by the sister sensor HSTOF of CELIAS/STOF on board SOHO (Figure 5). Hilchenbach *et al.* (1998) argued that other possible sources can be excluded, so that the energetic H atom fluxes during quiet times are identified as heliospheric energetic atoms. These particles are most likeley coming from the heliosheath, thus constituting the first detection of energetic neutral atoms originating beyond the TS of the solar wind.

Hsieh *et al.* (1992) have modeled this particle flux using the ACR protons accelerated at the TS as source. A much improved calculation by Czechowski *et al.* (1995), including the convection and diffusion of the ACRs in the heliosheath

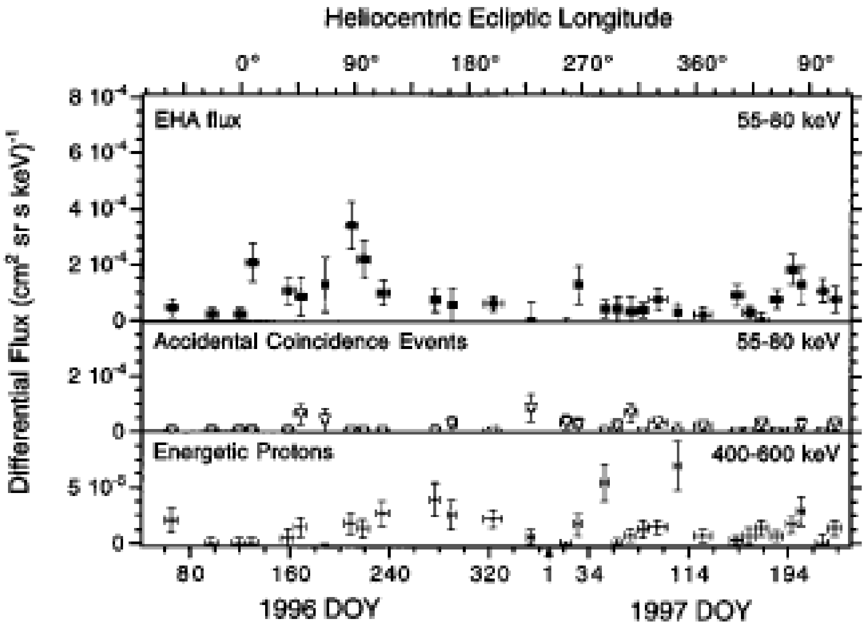

Figure 5. Differential flux of quiet-time 55–80 keV energetic H atoms as observed by HSTOF after background subtraction (*upper panel, filled squares*). For comparison, the background level (*middle panel, open triangles*) and the energetic proton fluxes (*bottom panel, solid crosses*) are plotted for the same quiet times (from Hilchenbach *et al.*, 1998).

region bounded by the TS and the heliopause, indicates the observed strong anisotropy in the energetic H atom flux in the antiapex direction of the heliotail.

5. Conclusions

Spacecraft measurements provide a precise tool to study elemental and isotopic abundances, transport and acceleration, and origin of pick-up ions in the heliosphere. The heliospheric pick-up ions from the different sources such as the interstellar gas, the distributed Inner Source, and the planetary and cometary components are distinguished by their velocity distributions. These distributions depend 1) on the initial velocity distributions of the neutral particle sources before ionization by solar ultraviolet radiation, and 2) on the transport and acceleration of the pick-up ions in the Heliospheric Magnetic Field and the solar-wind plasma.

With measurements on interstellar pick-up ions the composition, density, and the magnetic field strength of the Local Interstellar Cloud have been determined. Furthermore, the dynamics of the interstellar gas in the Local Interstellar Cloud, in the filtration region beyond the heliopause, and in the inner and middle heliosphere have been explored. Data on $^4He^+$ pick-up ion fluxes at 1 AU represent the structure of the Interplanetary Focusing Cone formed by the interstellar gas flow in the Sun's gravity field. The $^4He^+$ pick-up ion cone at 1 AU can be shifted eastward in ecliptic longitude and widened by up to several degrees with respect to the neutral ^4He cone. This is a consequence of streaming of the pick-up ions along the Heliospheric Magnetic Field with a large mean free path for pitch-angle scattering of up to 1 AU. Considering this effect, the measured width of the $^4He^+$ Focusing Cone indicates an upper limit of the neutral ^4He temperature in the Local Interstellar Cloud of $\sim$ 7000 K.

Pick-up ions from the distributed Inner Source are particles released from interstellar and interplanetary dust inside the heliosphere and thus provide information on the spatial distribution of the dust. Planetary and cometary pick-up ions are a minor component but can serve as indicators for the transport of pick-up ions in the heliosphere.

All species of pick-up ions are extremely favored over solar-wind ions for injection into interplanetary energetic particle events. Thus, they constitute the dominant seed particle population for the Anomalous Cosmic Rays re-accelerated at the Termination Shock. During solar minimum the particles accelerated by Co-rotating Interaction Regions are dominant, whereas during activity maximum the pick-up ions accelerated in interplanetary Coronal Mass Ejections play an important role.

Besides the interstellar pick-up ions the Inner-Source pick-up ions need to be considered when interpreting the abundances of the Anomalous Cosmic Rays. The Anomalous Cosmic Rays are of limited use for precisely determining the abundances of interstellar matter because of the myriad effects during transport, injection and (pre-)acceleration in the heliosphere. However, knowledge about these fractionation processes is applicable to interprete the abundances of Galactic Cosmic Rays.

The energetic neutral H fluxes observed with the CELIAS/HSTOF sensor on board SOHO provided for the first time a diagnostic tool to analyze the structure in ecliptic longitude of the interface region between the heliosphere and the Local Interstellar Cloud by direct in-situ particle measurements unaffected by the Heliospheric Magnetic Field. These fluxes are enhanced in the upstream and downstream directions of the interstellar wind.

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