11

Suprathermal Particle Populations in the Solar Wind and Corona

M. Lazar[1], R. Schlickeiser[1] and S. Poedts[2]
[1]*Institute for Theoretical Physics, Institute IV: Space and Astrophysics, Ruhr-University Bochum, Bochum*
[2]*Centre for Plasma Astrophysics, Leuven*
[1]*Germany*
[2]*Belgium*

1. Introduction

Understanding and predicting the transport of matter and radiation in the solar wind and terrestrial magnetosphere is one of the most challenging tasks facing space plasma scientists today. Space plasmas are hot ($T > 10^5$ K) and poor-collisional (mean free path $\sim$ 1 AU), and contain ample free kinetic energy of plasma particles. Kinetic effects prevail leading to wave fluctuations, which transfer the energy to small scales: wave-particle interactions replace Coulomb collisions and enhance dispersive effects heating particles and producing suprathermal (non-Maxwellian) populations.

The existence of suprathermal distributions of charged particles has been regularly confirmed at any heliospheric distance in the solar wind and near Earth space by the spacecraft missions since the early 1960s (Feldman et al., 1975; Fisk & Gloeckler, 2006; Maksimovic et al., 1997a; 2005; Montgomery et al., 1968; Pilipp et al., 1987). Both deviations from isotropy and from thermal equilibrium are in general well explained by the action of plasma wave fluctuations, which seem to be the best agent in the process of conversion and transfer of the free energy to suprathermal populations. Even for the quiet times, the dilute plasma in the solar wind does not easily reach thermal equilibrium because the binary collisions of charged particles are sufficiently rare. Distributions with high energy suprathermal tails are therefore expected to be a characteristic feature for any low-density plasma in the Universe.

Processes by which suprathermal particles are produced and accelerated are of increasing interest in laboratory an fusion plasma devices, where they are known as the *runaway* particles decoupled from the thermal state of motion, and for a wide variety of applications in astrophysics. The astrophysical phenomena generally appear to involve an abundance of suprathermal ions and electrons observed to occur in the interplanetary medium, and which provide information about their source, whether it is the Sun or from the outer heliosphere. Accelerated particles (including electrons, protons and minor ions $^4He^{+2}$, $^{16}O^{+6(+7)}$, $^{20}Ne^{+8}$) are detected in the quiet solar wind and terrestrial magnetosphere, and in the solar energetic particle (SEP) events associated with flares and coronal mass ejections (CMEs) during intense solar activity (see discussions and references in Lin (1998) and Pierrard & Lazar (2010)). A steady-state suprathermal ion population is observed throughout the inner heliosphere with a velocity distribution function close to $\propto v^{-5}$ (Fisk & Gloeckler, 2006), and, on the largest scales, the relativistic cosmic-ray gas also plays such a dynamical role through the galaxy and its halo (Schlickeiser, 2002).

Solar wind distributions of charged particles comprise two different populations: a low energy thermal core and a suprathermal halo, and both are isotropically distributed at all pitch angles (Maksimovic et al., 2005; Montgomery et al., 1968). In the fast solar wind, the halo distribution can carry a magnetic field aligned strahl population, which is highly energetic and usually antisunward moving (Marsch, 2006; Pilipp et al., 1987). Suprathermal particles are present not only in electron distribution functions (Fig. 1) but in many ion species including H^+, He^{++}, and the heavier ions (Ne, N, O) present in the solar wind (Chotoo et al., 2000; Collier et al., 1996).

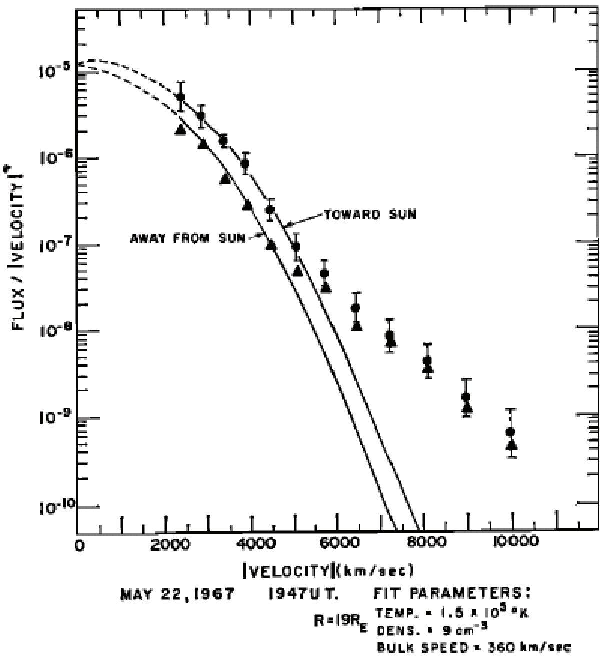

Fig. 1. Empirical distribution functions of the solar wind electrons measured at ~ 1 AU by the Vela 4B satellite, and the Maxwellian fit (solid lines) to the low-energy data. Non-Maxwellian tails of the suprathermal electrons are clearly visible (after Montgomery et al. (1968)).

In this chapter we review the observational inventory of suprathermal populations, and present the theoretical and numerical techniques used to interpret and explain their origin in the solar wind, corona and some planetary environments. Recently, a short review of the theories and applications of Kappa particle distribution functions, has been provided by Pierrard & Lazar (2010), which only partly covered these aspects. The many spacecraft missions and observational reports of the last decades have greatly enhanced our knowledge about the existence of suprathermal populations in the solar wind. But their origin is still an open question because the multitude of models proposed to explain the acceleration of suprathermal particles are not always correlated with the observations. Understanding these mechanisms is essential for understanding key processes like heating in the corona and acceleration in the solar wind.

2. The observational evidence

The solar wind is the first, and up to now, the only stellar outflow to have been measured *in-situ* revealing important clues about the existence and the evolution of suprathermal particles, and their intimate connection to plasma wave turbulence and solar events.

2.1 The power-law Kappa model

The Kappa (or Lorentzian) function is a power-law generalization

$$f_\kappa(v) = \frac{1}{(\pi w_\kappa^2)^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma\left(\kappa - \frac{1}{2}\right)} \left(1 + \frac{v^2}{\kappa w_\kappa^2}\right)^{-(\kappa+1)} \quad (1)$$

$$w_\kappa^2 = \left(1 - \frac{3}{2\kappa}\right)\left(\frac{2k_B T}{m}\right) \quad (2)$$

introduced to describe suprathermal velocity distribution functions (Fig. 2) in plasmas out of thermal equilibrium (Maksimovic et al., 1997a; Vasyliunas, 1968). Here w_κ is the effective thermal velocity of the charged particles, m is the mass, n is the number density, T is the effective temperature, and $\Gamma(x)$ is the Gamma function. We call it a generalization because in the limit of a large power index, $\kappa \to \infty$ ($w_{\kappa\to\infty} = v_T = \sqrt{2k_B T/m}$), the power-law distribution function reduces to a Maxwellian, $f_\kappa(v) \to f_M(v)$ (red line in Fig. 2).

According to the form (1) of the Kappa distribution function, the power index κ must take values larger than a minimum critical value $\kappa > \kappa_c = 3/2$, for which the distribution function (1) collapses and the effective temperature is not defined. The distributions observed in the solar wind and terrestrial environments have been fitted with Kappas in this range. Furthermore, the velocity moments of the Kappa distribution functions can be defined only to the orders less than $\kappa + 1$, enabling a macroscopic description of the plasma with at least three moments of the Kappa distribution, the mean particle density, the streaming velocity and the effective temperature. The power index κ determines the slope of the energy spectrum of the suprathermal particles forming the tail of the velocity distribution function.

In collisionpoor or collisionless plasmas the independence of particles breaks down due to long-range correlations mediated by the plasma waves, and classical statistics cannot provide a basic derivation for Kappa distributions. Power-law distributions result instead from a new generalized statistics (Tsallis, 1995) for charged particles with long-range correlations supplied by the (quasi-stationary) field turbulence. Long-range correlations contribute to a super-extensive entropy (Leubner, 2002; Treumann & Jaroschek, 2008; Tsallis, 1995) implying generalization of the plasma temperature to non-thermal quasi-stationary states (Leubner, 2002; Livadiotis & McComas, 2009), and providing fundamental justification for Kappa distribution functions. Thus, the role of these distribution functions becomes of great significance not only in plasma physics and astrophysics, but generally, in electrodynamics and statistics.

When particle distributions measured in the solar wind are fitted with Kappa functions the power index κ for the electrons ranges from 2 to 5, and takes even larger values for protons

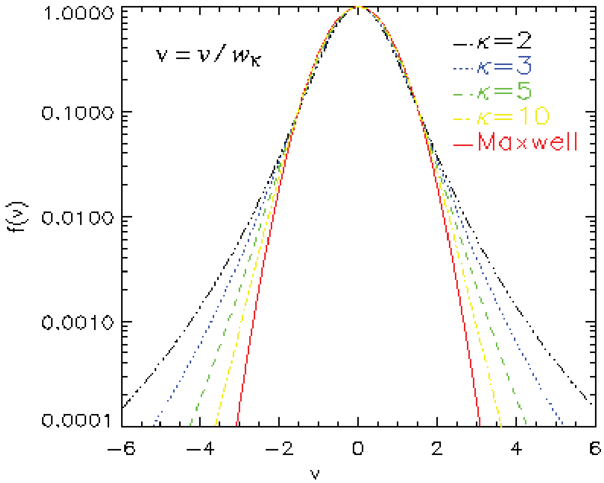

Fig. 2. Kappa distribution functions approach a thermal Maxwellian core at small velocities, less than thermal speed $v \ll w_\kappa$, but enhances showing superthermal tails at high energies, $v > w_\kappa$ (after Pierrard & Lazar (2010)).

and heavier ions (Pierrard & Lazar, 2010). As radial distance from the Sun increases and there are fewer collisions, the velocity distribution functions exhibit stronger suprathermal tails and values of the fitted power index κ decrease with distance, see Fig. 3 (Maksimovic et al., 2005). A sum of two Maxwellians has also been proposed to fit with the observations, but the best fit of the overall particle distribution including suprathermal tails is obtained using only one Kappa distribution function (Maksimovic et al., 1997a; Zouganelis et al., 2004). This needs, by comparison to two Maxwellians, a reduced number of macroscopic parameters (density, streaming velocity, temperature, and power index κ) to describe the plasma state.

Energy (or velocity) distribution functions of electrons and ions are frequently measured in space with electrostatic analyzers. These instruments measure three dimensional distributions, and can provide energy, mass and charge composition of the suprathermal populations. The quantity measured is the particle flux, namely the differential particle flux $J(W, \alpha, \vec{r})$ per unit area at given energy (W), pitch angle (α), and position ($\vec{r}$). This is the flux of particles measured in a certain energy interval, and which directly relates to the distribution function by

$$J(W, \alpha, \vec{r}) = \frac{v^2}{m} f(v_\parallel, v_\perp, \alpha, \vec{r}). \tag{3}$$

Measuring techniques have considerably been improved in the last decades. The quasi-thermal noise spectroscopy is a powerful tool for in situ space plasma diagnostics based on the analysis of the electrostatic field spectrum produced by the quasi-thermal fluctuations of electrons (Chateau & Meyer-Vernet, 1991; Le Chat et al., 2009; Zouganelis, 2008). The quasi-thermal noise is produced by the quasi-thermal fluctuations of the electrons and by the Doppler-shifted thermal fluctuations of the ions. The electron density and temperature are measured accurately since the quasi-thermal noise spectroscopy is less sensitive to the spacecraft perturbations than particle detectors. Measuring the noise peak just above the plasma frequency $\omega_p^2 = 4\pi ne^2/m$ allows an accurate evaluation of the plasma density n. In addition, since the peak shape strongly depends on the velocity distribution of electrons, the analysis of the spectrum reveals its properties, for instance, the temperature or the value of the power index κ when the fitting model is chosen to be a Kappa function. In contrast to a Maxwellian, for a power-law tail the peak is exactly at the plasma frequency. Despite the measuring constraints of the high-energy electron parameters (the plasma density fluctuations can broaden the spectral peak if the frequency/time resolution of the receiver is not high enough) the kappa parameter deduced with data from Ulysses is mainly in the range 2 - 5 indicating the presence of conspicuous suprathermal tails and agreeing with the results by Maksimovic et al. (1997a), who fitted the SWOOPS electron distribution functions on Ulysses and found a Kappa within the same range of values (Zouganelis, 2008).

2.2 Suprathermal electrons in the solar wind and terrestrial magnetosphere

Suprathermal electrons observed at different helisopheric distances in the solar wind and in the planetary environments have been fitted with suprathermal Kappa distributions with a power index $2 < \kappa < 6$ (Gloeckler & Hamilton, 1987; Maksimovic et al., 1997a). Helios I and II (before 1985) and the Wind missions (after 1994) provided measurements of electrons between 0.3 AU and 1 AU, and Ulysses (before 2009) from large heliocentric orbits over 1 AU to 5 AU. In terrestrial magnetosphere the first reports on the existence of suprathermal electrons came from the OGO missions in '60s-'70s, and then from the Cluster (after 2000) and Wind missions for all distinct regions including the plasmasheet, the magnetosheath and the radiation belts. Data provided by Helios, Ulysses, Cassini, Wind and the *Hubble Space Telescope* have also shown the existence of suprathermal electrons in the magnetosphere of other planets, like Mercury, Jupiter, Saturn, Uranus, Neptune, Titan (see Pierrard & Lazar (2010) and references therein).

The electron distributions are directly or indirectly measured in the solar wind and corona and show a global anticorrelation between the solar wind bulk speed and the value of the parameter κ: the high speed streams with important bulk velocities are emitted out of coronal regions where the plasma temperature is lower, and the low speed solar wind is originating in the hotter equatorial regions of the solar corona. Radial evolution of nonthermal electron populations in the low-latitude solar wind have been measured with Helios, Cluster, and Ulysses. The observations show a decrease of the relative number of strahl electrons with distance from the Sun, whereas the relative number of halo electrons is increasing (Maksimovic et al., 2005; Stverak et al., 2008). Further out in the solar wind, while the core density is roughly constant with radial distance, the halo and strahl densities vary in an opposite way (Maksimovic et al., 2005) indicating that suprathermal halo population consists partly of electrons scattered out of the strahl by broadband whistler fluctuations (Stverak et al., 2008).

Enhanced fluxes of suprathermal electrons have frequently been reported by the Ulysses mission upstream of co-rotating forward and reverse shocks in the solar wind at heliocentric distances beyond 2 AU (Gosling et al., 1993). The average duration of these events, which are most intense immediately upstream from the shocks and which fade with increasing distance from them, is ~ 2.4 days near 5 AU. The observations suggest that conservation of magnetic moment and scattering typically limit the sunward propagation of these electrons as beams to field-aligned distances of ~ 15 AU.

The solar wind halo includes electrons of energies over 100 eV to 1 keV, and is believed to originate from coronal thermal electrons which have a temperature of $\sim 10^6$ K (Lin, 1998). This spectrum referred to as the quiet time *primary* flux of suprathermal electrons appears to have a solar origin because it is measured in the absence of any solar particle events, and electrons of such energies are continuously escaping from the Sun being present in both the fast and slow solar winds. Primary fluxes of energetic ions are generally lower, possibly because at coronal temperatures ions are gravitationally bounded while electrons not.

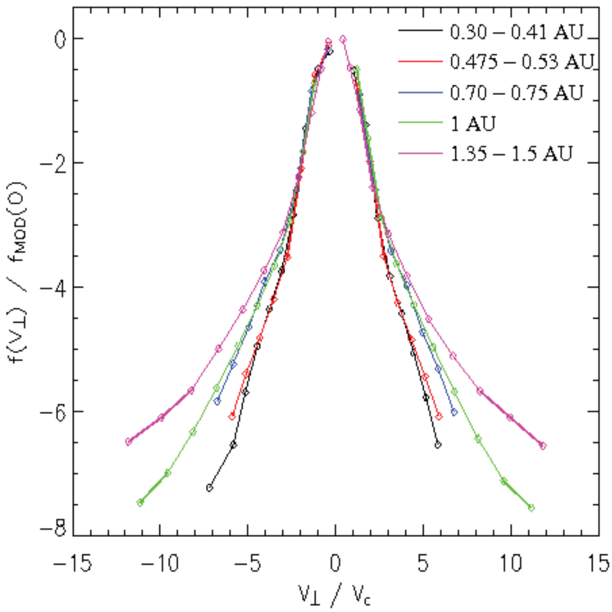

Fig. 3. Distribution function of the solar wind electrons for different heliospheric distances: the normalized core component remains unchanged at all radial distances while the relative number of halo electrons compared to the one of the core, increases with radial distance (after Maksimovic et al. (2005)).

The ion charge measurements stated by Ulysses in times of higher activity of the Sun, were found to be consistent with coronal Kappa distributions of electrons with kappa index ranging between 5 and 10. The presence of non-Maxwellian electron energy distributions in the solar transition region is suggested by the Si III line ratio from SUMER (Pierrard & Lazar (2010) and some references therein). Coronal origin of the energetic particles is also sustained by their traces in the emissions of solar flares and adjacent coronal sources (Kasparova & Karlicky, 2009). Observations in the corona suggest distributions having a nonthermal character that increases with altitude. Observations of electron suprathermal tails in the solar wind suggest their existence in the solar corona, since the electron mean free path in the solar wind is around 1 AU. Numerical computation of the velocity distribution function evolution from the profile measured at 1 AU back to the solar corona, supports a plausible coronal origin of the suprathermal populations (Pierrard et al., 1999).

There is also large observational evidence indicating that the formation of suprathermal fluxes is closely related to an enhanced activity of plasma waves and instabilities. The primary (coronal) flux of suprathermal particles is the source population for particles accelerated to higher energies by the impulsive solar energetic events at the site of flares, or by the gradual large SEP (LSEP) events in interplanetary CME-driven shocks (Ergun et al., 1998; Lin, 1998). Thus, a *secondary* flux of highly energetic called super-halo, electrons up to 2-100 keV and protons up to 10 MeV, will enhance the solar wind suprathermals which would have been originally accelerated in the corona and hence bear distinctive compositional and energetic features.

2.3 Suprathermal ions in the solar wind and terrestrial magnetosphere

The *Wind* mission has provided elemental and isotopic abundances for the solar wind ions near 1 AU, including temperatures, charge state distributions and reduced distribution functions, which extend well into the suprathermal tails (Collier et al., 1996). ^{4}He, ^{16}O, and ^{20}Ne distribution functions averaged over many days all appears well-fitted by Kappa functions (see Figure 4) with sufficiently small values of the power index $2.4 < \kappa < 4.7$. The average ^{4}He/^{20}Ne density ratio is 566 ± 87, but has significant variability with solar wind speed, and the average ^{16}O/^{20}Ne density ratio is 8.0 ± 0.6. The average ^{20}Ne/^{4}He and ^{16}O/^{4}He temperature ratios are close to unity at low solar wind speeds, but increase with the solar wind speed. Non-Maxwellian particles were also reported in H^{+}, He^{++}, and He^{+}

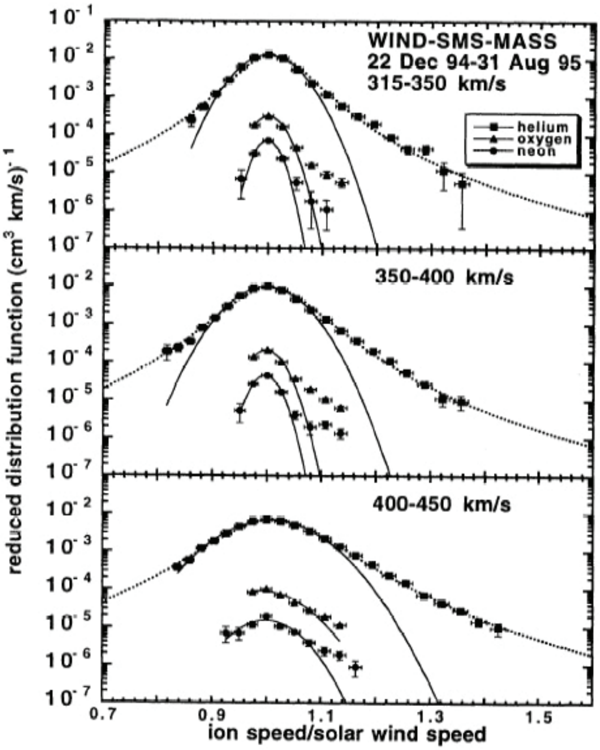

Fig. 4. Ion distribution functions measured at 1 AU in the solar wind (after Collier et al. (1996)).

distribution functions during co-rotating interaction region (CIR) events observed by *Wind* at 1 AU (Chotoo et al., 2000).

Primary fluxes of suprathermal ions recorded during a solar minimum are in general much lower than the electron fluxes (Lin, 1998), because at coronal temperatures the ions are gravitationally bounded while electrons not. For the same reason an ambipolar electric field (the Pannekoek-Rosseland field) is set up and extends into the solar wind accelerating protons outward and decelerating electrons. This potential varies inversely with distance from the Sun, with total drop of about 1 kV from the base of the corona to 1 AU (Lin, 1998).

Data from the plasma and magnetic field instruments on *Voyager* 2 indicate that non-thermal ion distributions could have key roles in mediating dynamical processes at the termination shock and in the heliosheath (Decker et al., 2008). The LECP (Low Energy Charged Particle) detectors on both *Voyager* 1 and 2 have established that a power law describes the heliosheath ions downstream of the termination shock in the energy range of $\sim$ 30 keV to 10 MeV (see Decker et al. (2008) and references therein). It is not known where exactly in the energy spectrum the power law tail begins, but the energy region below 30 keV (including the low range $\sim$ 0.01 - 6 keV) has been investigated by the IBEX (Interstellar Boundary Explorer) mission (Prested et al., 2008). IBEX was designed to make the first global image of the heliosheath beyond the heliospheric termination shock measuring the energetic neutral atoms (ENAs) created on the boundary of our solar system by charge exchange between downstream protons and interstellar hydrogen atoms, and that cannot be measured by conventional telescopes. The first simulated ENA maps of the heliosheath have used Kappa distributions of protons and calculate the ENAs that are traveling through the solar system to Earth. Considering suprathermal protons is well motivated by a significant increase of the ENA flux within the IBEX low-energy range $\sim$ 0.01 - 6 keV by more than an order of magnitude over the estimates using a Maxwellian (Prested et al., 2008).

The observations of the *ACE* and the *Ulysses* missions have revealed suprathermal tails that are always present within the integration times of the observations, and with intensities increasing in the presence of interplanetary shocks and other disturbed conditions. In the quiet-time conditions, suprathermal, power-law tails, known as quiet-time tails, are also present, and at 1 AU the tails include solar wind ions with a spectral index of -5 (see Fisk & Gloeckler (2006) and references therein). In the observations beyond 1 AU, the tails can be dominated by accelerated interstellar pickup ions.

For the time of an active Sun, the suprathermal flux of ions can be enhanced by the large solar energetic particle (LSEP) events, which produce significant fluxes of $\gtrsim$ 10 MeV protons. These events usually occur after an intense solar flare, and occasionally exhibit acceleration up to relativistic energies. In interplanetary space, LSEP events are associated with interplanetary CME-driven shocks. Electrons are also observed, but the fluxes of energetic protons dominate over electrons. Tens of LSEP events are detected per year near solar maximum Lin (1998). Direct observations confirm that, at least at some times, solar wind suprathermals can be augmented by suprathermals from LSEP events (Mason et al., 1995). One plausible scenario is that suprathermal ions (e.g., ^{3}He) remnant from impulsive events (at the flare site) may be a source population available for further acceleration by interplanetary shocks that accompany large SEP events, thereby leading to the ^{3}He enhancements in a significant fraction of large SEP events. There is also evidence of heavier suprathermal ions, e.g., Fe, remnant from flares and present in the source population of LSEP events (Tylka et al., 2001).

3. The existing models for the generation of suprathermal populations

Velocity distribution functions with suprathermal tails observed in the solar wind can be the result of their existence in the lower solar corona and the velocity filtration mechanism in gravitational and electrostatic (ambipolar) fields in the upper solar atmosphere (Scudder, 1992). Postulating that suprathermal particle distributions populate the transition region between the chromosphere and the corona, the temperature will increase with height through velocity "filtration" of the particle distributions in gravitational/electrostatic fields without invoking any local heating source. The temperature profile derived from the second order moment of such a Kappa distribution function is an increasing function of height (Pierrard & Lamy, 2003). The energy flux carried by high-energy electrons may be transferred into flow energy in the supersonic region of the flow leading to an enhancement of the energy density and the asymptotic flow speed of the solar wind. The velocity filtration model predicts the evolution of the electron velocity distribution function at higher altitudes in the solar wind with three distinct components, the core, halo, and strahl populations, similar to those observed in the interplanetary space (Viñas et al., 2000).

However, the velocity filtration mechanism does not address the question of how to generate and maintain the suprathermal populations in the solar wind and corona. In the chromosphere, the suprathermal electron distributions can be generated by the transit-time damping of the fast-magnetosonic waves (Roberts & Miller, 1998). This mechanism might operate reasonably well in the low-collisional region of the chromosphere, but it is a slow process and will be quenched rapidly in regions where collisional damping is important (Viñas et al., 2000). A realistic approach of the possible answers on the origin of suprathermal populations in the solar wind and corona requires a kinetic analysis of the coronal heating processes and the solar wind acceleration.

The anisotropy of the particle velocity distributions in stellar winds is basically controlled by the Chew-Goldberger-Low (CGL) mechanism: as the wind expands, the plasma density and magnetic field decrease radially, and if the particle motion is adiabatic and collisionless, the distributions become anisotropic in the sense that the pressure (or temperature) along the magnetic field exceeds the perpendicular pressure (or temperature, $T_\parallel > T_\perp$). In the case of violent outflows generating interplanetary shocks after solar flares or CMEs, injection of particle beams into the surrounding ionized interplanetary medium creates additional beam-plasma or temperature anisotropy.

These large deviations from isotropy quickly relax by the resulting wave instabilities, which act either to scatter particles back to isotropy or to accelerate them (Landau or cyclotron resonance) and maintain a superthermal abundance because thermalization is not effective at these time scales. The energy dissipation is a sustained interchange of energy between particles and plasma wave fluctuations, eventually lasting over sufficiently large time scales to be observed. The high rate of occurrence of an excess of perpendicular temperature ($T_\parallel < T_\perp$) at large radial distances in the heliosphere (Kasper at al., 2002; Stverak et al., 2008) is a proof that wave-particle interactions must be at work there dominating over the adiabatic expansion.

In low-collisional plasmas transport of matter and energy is governed by the selfconsistent correlation between particles and electromagnetic fields, which can, for instance, convect charged particles in phase space but are themselves created by these particles. The resulting Kappa distribution functions represent therefore not only a convenient mathematical tool, but a natural and quite general state of the plasma (Pierrard & Lazar, 2010). Suprathermal

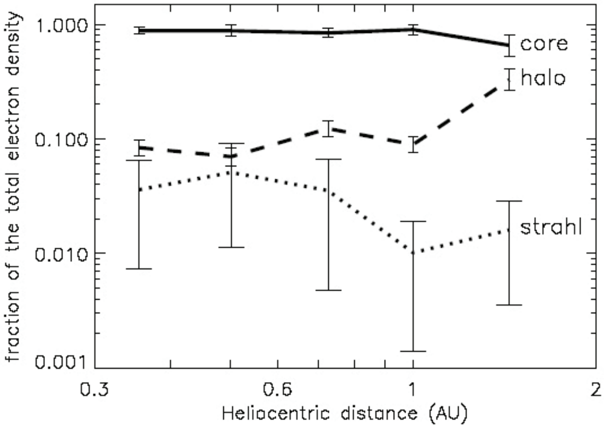

Fig. 5. Radial variations of the relative number density for the core (full line), halo (dashed line), and strahl (dotted line) populations, respectively, n_c/n_e, n_h/n_e, and n_s/n_e, where $n_e = n_c + n_h + n_s$. During the solar wind transport an important fraction of the strahl electrons may be diffused and transferred to the halo population (after Maksimovic et al. (2005)).

populations must therefore involve selfconsistently in both processes of wave turbulence generation and particle energization because the electromagnetic wave fields are the most efficient agent for charged particles energization. Stochastic acceleration of charged particles can account for both the momentum diffusion due to cyclotron or transit-time damping of the ambient electromagnetic fluctuations, and the momentum convection due to compression near shock waves in space (Schlickeiser, 2002). Unfortunately, none of these processes is well understood, mostly because these plasmas are poor-collisional and require progress in modeling the wave turbulence, going beyond MHD models to use a kinetic and selfconsistent description.

3.1 Models proposed for the acceleration of electrons

Looking to the observations reproduced in Fig. 5, the radial dependence in the solar wind shows an increasing number of the halo electrons, while the number of strahl electrons is decreasing with the distance from the Sun (Maksimovic et al., 2005). These observations suggest that the halo population consists partly of electrons scattered out of the strahl, and given the poor (particle/particle) collisionality of these populations, the mechanism that can explain their scattering is necessarily the interaction with plasma waves.

Cooling down of the suprathermal electrons originating in the corona due to a rapid adiabatic expansion in the interplanetary space would be also responsible for a decreasing in suprathermal populations, but in both components, the halo and the strahl, at the same time, and the effect should be an increasing of the core population. But such an evolution is not confirmed by the observations in Fig. 5, where the core relative number density remains roughly constant between 0.3 and 1.5 AU, that can be explained only by some some supplementary acceleration. Interactions with plasma waves would therefore be a plausible candidate to explain the scattering and isotropization of electrons from the strahl component (Pagel et al., 2007), as well as the acceleration of the low-energy electrons from the core (Ma &

Summers, 1999; Roberts & Miller, 1998), counterbalancing the cooling of suprathermals due to expansion.

Hasegawa et al. (1985) proposed the first wave-particle acceleration model showing that, although photons do not contribute directly to the velocity-space transport in a nonrelativistic plasma, an intense electromagnetic radiation can induce fluctuations in the Coulomb field enhancing the velocity space diffusion and producing a power-law distribution of electrons. The acceleration of plasma particles mechanism by wave-particle interaction is modeled within the Fokker-Planck formalism, where the velocity space diffusion is induced by the resonant Landau or cyclotron interactions.

Using the same kinetic formalism, but for a space plasma embedded into a stationary magnetic field, Ma & Summers (1999) have invoked the acceleration of electrons by the cyclotron resonance with whistlers. The turbulent spectrum of the whistlers has been assumed of Kolmogorov-type ($I \propto k_{\parallel}^{-q}$, $q = 5/3$) by extension of the wave-spectra observations from the inertial range. It was found that a very weak turbulence, with a very small power density of magnetic fluctuations $\delta B^2/B_0^2 < 10^{-7}$, can produce Kappa distributions of electrons with values of the index $\kappa = 2 - 8$ typically observed in the solar wind and magnetosphere.

Transit time damping of the low-frequency fast MHD oblique modes can also accelerate electrons and produce power law distributions in different conditions typical for solar flares and magnetosphere (Roberts & Miller, 1998; Summers & Ma, 2000). In the solar wind these waves arise in the acceleration region (the "reservoir") near the Sun, and interact and cascade to higher wavenumbers (the dissipation range) where eventually energize electrons out of an initially Maxwellian distribution. From the fast mode dispersion relation, the resonance condition can be written as $v_{\parallel} = v_A/\eta$ where v_A is the Alfvén speed, and $\eta = k_{\parallel}/k$. Hence, the threshold speed for the acceleration to occur is v_A, and electrons will therefore be preferentially energized, while only a negligible number of protons in the thermal tail can resonate (protons will, however, be accelerated less efficiently by Alfvén waves (Miller & Roberts, 1995)). Leubner (2000) has also shown that the main dynamics of the lower-hybrid and Alfvén waves-particle energy exchange due to Landau interaction, is regulated in a parallel direction with respect to the ambient magnetic field, providing the acceleration of electrons and the basis for the formation of (one-dimensional) Kappa distribution functions.

Such a model has systematically been invoked to explain the electron acceleration in a flaring solar coronal loop, where a spectrum of MHD waves is established by the primary energy release event, e.g., magnetic reconnection (De La Beaujardière & Zweibel, 1989; Miller, 1991). In such multiwave systems the stochastic acceleration leads to diffusion in the velocity space, and proceeds as long as the wave energy density exceeds the particle kinetic energy density. The behavior of a particle depends on whether or not it is in resonance with the wave spectrum, and the resonant particles follow chaotic trajectories and undergo diffusion in velocity space between wave effective potentials, thereby gaining energy (De La Beaujardière & Zweibel, 1989). The particle velocity spectrum can become very hard, with values of the power index κ below 4, in agreement with the observed non-thermal X-ray and radio emissions (Kasparova & Karlicky, 2009).

Primary fluxes of suprathermal populations originating in the corona and regularly observed in the quiet solar wind, can be reaccelerated to higher energies by the impulsive flares, or by the gradual large SEP events in the interplanetary CME fast shocks (Ergun et al., 1998; Lin, 1998) leading to the formation of a secondary (harder) flux of suprathermal populations. The electrostatic turbulence and the resulting electromagnetic decays (radio bursts) are produced by beams or counterstreaming plasmas and can be responsible for particle energization at these sites (Lin, 1998; Yoon et al., 2006). Marginally stable plateaued distributions coincide only occasionally with periods of local Langmuir emissions suggesting that competition of the electrostatic growing modes with whistlers and oblique mode instabilities may be important (Ergun et al., 1998).

Enhanced fluxes of suprathermal electrons reported by Ulysses beyond 2 AU seem to be caused by the leakage of shock heated electrons back into the upstream region of co-rotating forward and reverse shocks in the solar wind. These leaked electrons commonly counterstream relative to the normal solar wind electron heat flux. Although it seems unlikely that these shock-associated events are an important source of counterstreaming events near 1 AU, remnants of the backstreaming beams may contribute significantly to the diffuse solar wind halo electron population there (Gosling et al., 1993).

Strongly damped electrostatic modes are expected to be effective in processes of acceleration, but stochastic acceleration is typically slow due to the diffusive nature of the scattering process, and needs to be sustained. The nonlinear wave-wave and wave-particle interaction involving intense low-frequency Alfvén waves or electrostatic Langmuir and ion sound (weak) turbulence driven by the beam-plasma instabilities (Viñas et al., 2000; Yoon et al., 2006) can also be responsible for the acceleration in the corona, solar wind and magnetosphere. Instead of modeling it, Yoon et al. (2006) have proposed an advanced selfconsistent derivation of the wave intensity from a wave kinetic equation including spontaneous or induced emissions, wave-particle scattering and wave-decay processes for the electrostatic modes. In the upper regions of the solar atmosphere (in the presence of collisional damping) low-frequency, obliquely propagating electromagnetic waves can carry a substantial electric field component parallel to the mean magnetic field that can decay generating high-frequency plasma oscillations and low-frequency ion-acoustic waves. The resulting electrostatic modes would be rapidly damped out leading to the formation of suprathermal electron distributions near the Sun (Viñas et al., 2000). Due to large scale density fluctuations generated by the solar wind MHD turbulence, the Langmuir wave packets are trapped in the proton density holes leading to an efficient acceleration of electrons and formation of suprathermal tails (Califano & Mangeney, 2008; Yoon et al., 2006).

The nonlinear mechanisms of acceleration are usually investigated in numerical experiments, and the simulations indicate that the results of the quasilinear theory are applicable to the finite amplitude wave fluctuations typically observed in the solar wind and magnetosphere (Califano & Mangeney, 2008; Leubner, 2000; Roberts & Miller, 1998; Summers & Ma, 2000). It appears that the traditional quasi-linear theory provides a reasonable description of particle scattering and acceleration by a weak plasma turbulence. A quasilinear analysis is based on Boltzmann-Maxwell equations, and the resulting equations for the weak plasma turbulence include the kinetic equation for particle distributions (with Coulomb or wave-particle collisional terms) (Davidson, 1972; Yoon et al., 2006). While Coulomb collisions are not efficient in interplanetary space, the interaction with wave fields is the most promising leading to diffusion, pitch-angle scattering and acceleration of charged particles.

Two complementary kinetic models have been proposed to determine the heliospheric radial profiles of the distribution function and statistical moments starting either from coronal properties suggested by the observed emissions (Vocks & Mann, 2003; Vocks et al., 2005), or from more precise in-situ measurements at 1 AU in the solar wind (Pierrard et al., 2011; 1999; 2001). The whistler waves eventually present in the corona are an important ingredient supporting coronal origin of the superthermal electrons observed in the solar wind. Based on this hypothesis the kinetic model developed by Vocks & Mann (2003) can explain the formation of the aligned antisunward moving strahl in the fast wind. If the whistler turbulence is further present in the solar wind, the antisunward waves reduce the anisotropy making superthermal halo present at all pitch angles, and the sunward moving waves scatter electrons out of the strahl into the halo (Vocks et al., 2005) as suggested by the observations (Maksimovic et al., 2005).

Otherwise, Pierrard et al. (2011) have shown that the solar wind plasma parameters measured at 1 AU, including the temperature and the anisotropy of the suprathermal electrons, can be a consequence of the whistler turbulence action at lower altitudes in the solar wind. Radial profiles of the electron-whistler scattering mean-free-path (mfp) suggest that at large heliospheric distances ($r > 0.5$ AU) whistler turbulence should in general be more efficient than Coulomb collisions leading to pitch-angle diffusion (temperature anisotropy) and electron acceleration (suprathermal tails). Collisions constrain at lower distances ($r \ll 0.5$ AU), but their role is usually limited to isotropization, while the same estimations of the wave-particle scattering mfp are still favorable to a possible contribution of whistlers to the electron energization in the active region of corona (Pierrard et al., 2011) giving valuable support to the complementary models (Kasparova & Karlicky, 2009; Vocks & Mann, 2003).

3.2 Models proposed for the acceleration of ions

Non-Maxwellian features of the solar wind proton distributions, including kinetic anisotropies and suprathermal tails, confirm expectations from resonant interaction with ion-cyclotron waves (see Marsch (2006) and references therein). In the initial impulsive phase of the solar flares, long-wavelength Alfvén waves are generated by restructuring of the magnetic field. These waves nonlinearly cascade to high wavenumbers and reach the dissipation range, where they can energize protons out the tail of the thermal distribution (Miller & Roberts, 1995). Then, these suprathermal protons are promptly accelerated to higher (relativistic) energies by the longer wavelength waves already present in the wave spectrum, and can produce the observed gamma-ray lines in impulsive solar flares.

Pierrard & Lamy (2003) have shown that the preferential heating of heavy ions relative to the protons, found in the empirical measurements, can be explained by the velocity filtration effect. The velocity filtration effect can account for the ion heating and the bulk acceleration of the solar wind particles without taking into account additional effect of wave-particle interactions. Moreover, the exospheric models show that with sufficiently high temperatures, the heavy ions are accelerated to high velocities in the low corona. Thus, the velocity filtration might contribute to the puzzling high temperatures observed in the corona and reduce the need for other heating mechanisms. While the source of coronal plasma waves is not always clear, the velocity filtration model needs suprathermal populations already present in the corona, an assumption that still waits for an observational confirmation and a theoretical explanation. A heuristic justification is that coronal suprathermal particles are collision poor due to the Coulomb collision cross section decreasing as $\propto v^{-4}$, and escape therefore more easily from the inner corona.

The first theoretical analyses of the quiet-time suprathermal ion population $\propto v^{-5}$ in the inner heliosphere have attributed their origin to the random compression and re-acceleration by the interplanetary wave turbulence (Fisk & Gloeckler, 2006). Recently Jokipii & Lee (2010) have reconsidered these theories showing that the compressive acceleration process does not produce power-law velocity spectra with indices less than (i.e., softer than) -3. Moreover, stochastic acceleration by a natural spectrum of Alfvén waves and oblique magnetosonic waves, yields comparable acceleration rates but also, do not produce power-law distributions with indices less than -3. Conversely, the process of diffusive shock acceleration, responsible for energetic storm particle events, co-rotating ion events and probably most large solar energetic particle (SEP) events, readily produces power-law velocity spectra with indices in a range including the observed -5. Consequently, the quiet-time suprathermal ion population will be composed predominantly of remnant ions from these events as well as a contribution from impulsive SEP events (Jokipii & Lee, 2010).

4. Some open questions and conclusions

Since the first reports on the existence of suprathermal populations in the solar wind and terrestrial environments, a significant progress has been made in many directions including the new modern techniques of observation and interpretation, and the large variety of theories and models proposed to explain particles acceleration and formation of suprathermal distributions. These are non-Maxwellian plasmas out of thermal equilibrium, and therefore expected to behave much different from the standard Maxwellian. Theoretically, the effects of suprathermal populations on the wave dispersion and stability properties have been extensively studied using Kappa distribution functions, isotropic or anisotropic, including or not drifts, and always making contrast with Maxwellian models (see (Pierrard & Lazar, 2010) and references therein).

Thus, establishing a realistic correlation between measurements of the suprathermal populations and the associated wave fluctuations detected at the same intervals of time and the same locations in the solar wind, would involve not only a technical progress, but will provide an important support for a correct understanding of the role of plasma waves in the process of acceleration. Distinction must be made between the wave fluctuations driven by various kinetic anisotropies of the suprathermal populations (like beams or temperature anisotropy), and those originating from other further sources in the solar wind, but passing through the same suprathermal sample at the time of observation.

The radio plasma imagers on board of satellites can stimulate such plasma emissions and echoes, known as plasma resonances, which are then reproduced on plasmagrams. Because these resonances are stimulated at the electron cyclotron frequency f_{ce}, the electron plasma frequency f_{pe}, and the upper-hybrid frequency $f_{uh} = (f_{pe}^2 + f_{ce}^2)^{1/2}$, they are measured to provide the local electron density and magnetic field strength. Calculations of these resonances using dispersion characteristics based upon a nonthermal Kappa distribution function appear to resolve the frequency discrepancy between these resonances in the magnetosphere and those predicted by a Maxwellian model (Viñas et al., 2005).

These calculations based upon an isotropic Kappa model simply suggest that departures from the standard Maxwellian provided by the dispersion/stability theory of the Kappa distributed plasmas should be introduced in the future techniques of evaluation and parametrization of the suprathermal populations and their effects in the solar wind. Moreover, accurate measurements of the kinetic anisotropies of plasma particles and the resulting wave fluctuations (Bale et al., 2009; Pagel et al., 2007; Stverak et al., 2008) can provide further support for theoretical modeling. The anisotropic Kappa distribution functions proposed to model kinetic anisotropies of the suprathermal particles are presently under debate because of the contradictory results provided by the existing models, namely, the bi-Kappa and the product-bi-Kappa functions (including or not drifts), with respect to the standard bi-Maxwellian (Lazar et al., 2010; 2011a). Correlating the empirical fitting data and the results from numerical experiments might be a valuable starting point for more comprehensive models developed to explain a full 3D formation of suprathermal populations in the solar wind.

The strahl component is the main contributor to the (electron) heat flux and the main contributor to the anisotropy of suprathermals, apparently a manifestation of the adiabatic focusing. Solar wind observations show that suprathermal strahl electrons have a width of the pitch angle distributions that decreases with increasing electron kinetic energy up to a few hundred eV (Pilipp et al., 1987), and becomes broader for more energetic electrons up to 1 keV (Pagel et al., 2007). Such a diversity implies a diversity of scattering mechanisms for the suprathermal strahl. The highly anisotropic strahl with $T_{\parallel} \gg T_{\perp}$ might be a driver of the firehose low-frequency wave instability, which can contribute to the electron scattering, but the firehose instability based on a bi-Maxwellian model requires a sufficiently large $\beta_{\parallel} > 1$, a condition rarely satisfied by the tenuous strahl. A simple bi-Kappa model incorporating all components, thermal and suprathermal, with the same averaged values for the particle density and the power index Kappa, requires even larger values of the plasma $\beta_{\parallel}$ (Lazar et al., 2011b). But a refined Kappa model accounting for a realistic, finite relative density of the halo and strahl components would probably provide better chances for this instability to develop confirming expectations from the observations, which indicate a constant presence of the corresponding magnetic field fluctuations in the solar wind (Bale et al., 2009; Stverak et al., 2008).

At smaller wavelengths, a second possible source of electron scattering are the whistler waves (Pagel et al., 2007), but their origin in the solar wind is not always understood. In the quiet solar wind conditions, the simulations show that enhanced whistler waves with finite damping lead to strahl pitch angle distributions which broaden in width with increasing kinetic energy, in agreement with observations, but at the same time, the strahl is broadened as a function of wave amplitude and relative strahl density (Saito & Gary, 2007). In addition, for the times the solar wind is disturbed by the electron radio bursts, the electrostatic electron/electron (two-stream) instability driven by a strahl with a large average speed leads to substantial strahl velocity scattering perpendicular to mean magnetic field. If the strahl speed is large compared to the halo thermal speed, after instability saturation, the width of the electron pitch angle distribution exhibits a maximum as a function of electron energy (Gary & Saito, 2007). Numerical experiments have also shown possibility to switch from focusing to scattering in the model of formation of the strahl/halo (including eventually, the superhalo) configuration due to a simple geometric effect of the Parker spiral magnetic field (Owens et al., 2008). Further out from the Sun, the pitch-angle scattering dominates because focusing of the field-aligned strahl is effectively weakened by the increasing angle between the magnetic field direction and intensity gradient, a result of the spiral field.

The results presented here emphasize the importance of studying these suprathermal plasma populations by not only the quantity of observations that attest their presence in all species of charged particles in the solar wind and terrestrial environments, but the exclusive and invaluable nature of informations about the natural plasmas out of thermal equilibrium. Understanding mechanisms by which suprathermal particles are produced and accelerated is essential for understanding key processes, like heating in the corona and acceleration in the solar wind. The central conclusion of our comparative analysis is that these topics clearly need further investigations to confront numerical simulations with the observations and make them consistent with dispersion and stability properties of the most appropriate suprathermal Kappa models.

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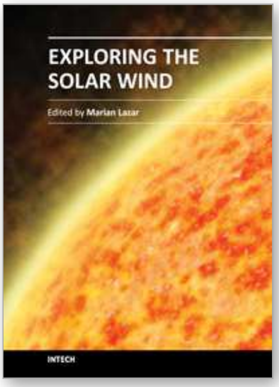

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This book consists of a selection of original papers of the leading scientists in the fields of Space and Planetary Physics, Solar and Space Plasma Physics with important contributions to the theory, modeling and experimental techniques of the solar wind exploration. Its purpose is to provide the means for interested readers to become familiar with the current knowledge of the solar wind formation and elemental composition, the interplanetary dynamical evolution and acceleration of the charged plasma particles, and the guiding magnetic field that connects to the magnetospheric field lines and adjusts the effects of the solar wind on Earth. I am convinced that most of the research scientists actively working in these fields will find in this book many new and interesting ideas.