A Review of Solar Wind Ion and Electron Plasma Distributions: Present Understanding and Ulysses Results

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Abstract Unlike the oral version of this paper at Solar Wind 8, this written version is not intended as an overview of the observational aspects of solar wind ion and electron distributions, but discusses only recent results in this area with emphasis on Ulysses measurements. Although primarily a review, some new results on solar wind proton temperatures at high latitudes are presented,

Introduction

Some recent observational aspects of solar wind ion and electron distributions are reviewed. Topics discussed are multiple ion beams in the solar wind, temperature and heating of solar wind ions, the electron distribution and indications of processes that may be limiting electron heat flux, and how shocks and magnetic mirrors affect the properties of the electron distribution. For a current comprehensive review of solar wind kinetic observations and theory, see *Feldman and Marsch*, 1995. Other excellent sources are some of the articles in the book on the inner heliosphere edited by *Schwenn and Marsch* (1991).

Ion Observations: Secondary Beams

A topic of particular interest is the origin of the double streaming of protons and alpha particles that is observed in the solar wind, In the high speed wind, what is typically observed at 1 AU is the presence of two protons beams with the higher speed beam being of lower density and traveling faster by roughly the Alfvén speed, Concurrently, alpha particles are typically observed as a single beam also traveling faster than the solar wind speed by about the Alfvén speed, In the lower speed solar wind typically single proton and alpha particle beams traveling at the same speed are observed; this may be attributed to the lower temperatures, higher densities and higher Coulomb collision rates in the low speed solar wind, However, at times double streaming is observed in the low speed solar wind, and in these cases, unlike the high speed wind, two alpha particle beams are observed to be present. The alpha particle abundance in the low speed plasma is typically less than that in the higher speed plasma in such cases, An example of the evolution in the trailing edge of a high speed stream from the high speed situation in which only one alpha particle beam is present to the low velocity situation in which two such beams are present is shown in Fig. 1 (from *Feldman et al.,* 1993).

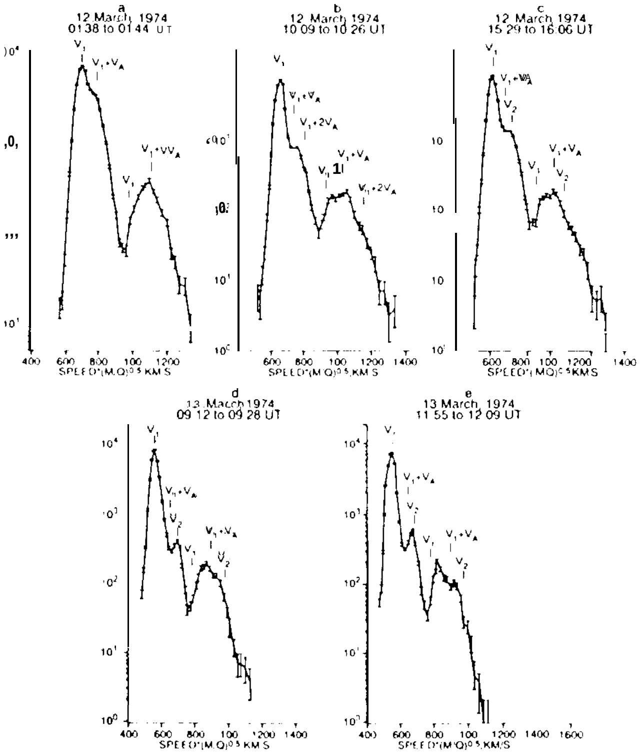

Figure 1. One-dimensional solar wind ion spectra measured within the high speed portion of a stream that passed the Earth between March 9 and 13, 1974. The earliest spectrum is at top left, thence to the right, then down with the last spectrum at bottom right, The first spectrum was measured near the beginning of the high speed stream, the last was well into the trailing edge. Speed is in units of km/s $(m/q)^{0.5}$. V_1 denotes the position of the proton peak, if there is a secondary beam with velocity substantially different than V_1+ VA it is denoted by V_2.

A correct understanding of the double streaming of solar wind ions would provide us information on the origin and transport of the solar wind. It should be noted that proton double streaming is probably of different origin than that of Helium. Helios observations at 0.3 AU generally do not indicate the presence of a secondary proton beam in a high speed stream (*Marsch et al.*, 1982a). Rather, a proton strahl is typically present which evolves into a secondary beam with increasing distance from the Sun. Both the strahl and the later forming secondary beam can be understood on the basis that faster particles have smaller Coulomb cross-sections and run away from the bulk of the distribution (*Livi and Marsch,* 1987).

The situation with respect to Helium ions is quite different; the Helium beam is typically traveling faster than the primary proton beam by about the Alfvén speed, and must have been accelerated in some fashion. A possible explanation is preferential absorption of ion cyclotron waves close to the Sun by Helium (the lower gyrofrequency of Helium might absorb wave energy before it cascades to higher frequencies where it is available to protons). A limit on this process is that Helium will be accelerated so that it is no longer in resonance with the coronal waves. This general topic, including warm plasma and heavy ion effects on the dispersion relation are discussed by *Isenberg (1984)*, and references therein, who concludes that this process may be feasible but is not as obviously correct as one might first think. *Feldman et al.* (1993) instead argue that the high speed heavy ion beams result from explosive jetting of material in bursts from the near vicinity of the Sun with the jets becoming a uniform beam during the transit to the Earth.

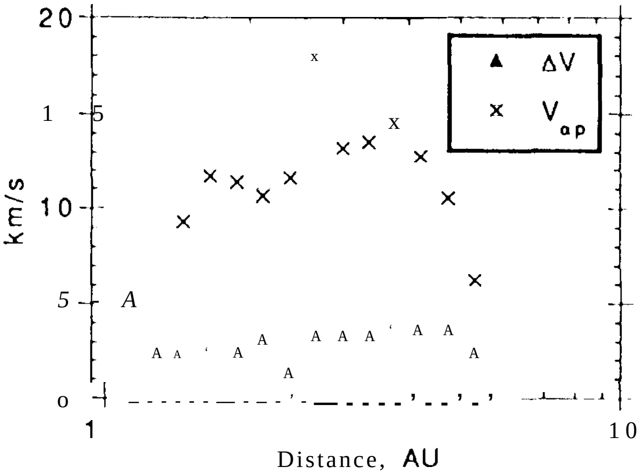

Figure 2. Averages of $\Delta V = |V_\alpha| - |V_p|$ and $V_{\alpha p} = |V_\alpha - V_p|$ calculated over radial bins of log R(AU) =0.05. Note that there is no correlation of either quantity with distance from the Sun,

Marsch et al, (1982b) report on Helium ions measured by the Helios spacecraft from 0.3 to 1.0 AU. These observations are of particular interest for several reasons, First, they found that often the He ions did not participate in the transverse motion of Alfvén waves in the solar wind. At these times the He ions were moving with approximately the Alfvén speed along the field with respect to the protons, The parallel differential streaming between alpha particles and protons was correlated with the solar wind speed, with values of the velocity difference as large as the Alfvén speed being attained only in the very high speed solar wind (see *Marsch et al.*, 1982ab). More recently, *Neugebauer et al, (1994)* reported observations of relative streaming in the ecliptic from 1.15 to 5,40 AU, and find that the correlation of parallel velocity difference with Alfvén speed disappears by 2 AU. Additionally, *Neugebauer et al.* also find (see Fig. 2) that there is no radial gradient in the differential streaming beyond about 1.5 AU. This may be contrasted with the notable gradient in the inner heliosphere (*Marsch* et *al.*, 1982b). *Neugebauer et al.* report that differential streaming beyond 2 AU is typically enhanced downstream of forward and reverse shocks. At high latitudes, *Goldstein et al.* (1995a) find that relative streaming gets as large as 1.2 times the Alfvén speed, and that the He ions have transverse motions comparable in magnitude but opposite in direction to that of the protons, indicating that the effective wave propagation speed is significantly less (by about a factor of about 0.6) than can be explained theoretically. They speculate that if pickup ions were not rapidly scattered in the solar wind, there might be sufficient pressure anisotropy to account for these observations. Earlier in-ecliptic work did not determine wave speed, but the ratio of velocity fluctuation to magnetic field fluctuation found in the ecliptic plane is less than calculated from theory, but with a smaller difference than found at high latitudes.

Ion Observations: Temperature Gradients and Heating

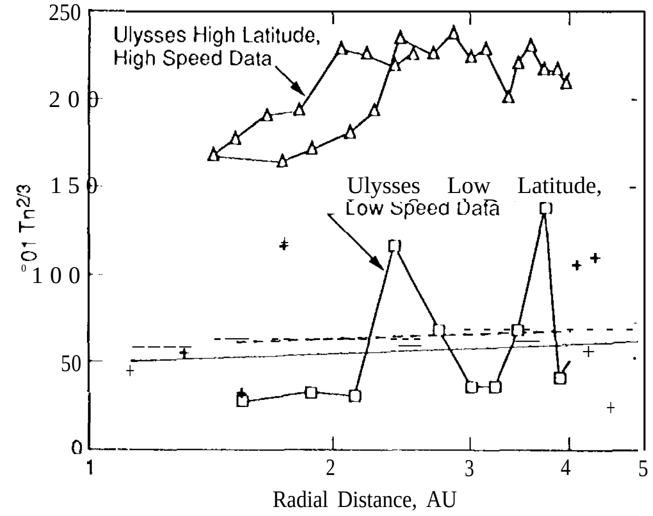

Figure 3. Values of the adiabatic constant, $T/n^{2/3}$. Pioneer estimates (*Bavassano* et *al.*, 1986) are shown as + symbols, SWOOPS in-ecliptic results are shown as squares, and SWOOPS high latitude results are shown as triangles, The straight lines are a linear least squares fit to the Pioneer data by *Tu et al.* (1987).

We use data from the Ulysses SWOOPS plasma experiment (*Bame* et *al.*, 1992) to obtain a radial gradient of the proton adiabatic constant, $T/n^{2/3}$. To study solar wind heating, we excluded periods containing Coronal Mass Ejections, shocked plasma, magnetic clouds, and bi-directional electron streaming. Averages of plasma parameters over solar rotations were performed, The Ulysses temperature results are based on the total temperature of the protons, including energy due to relative motion between primary and secondary beams if such are present (note, a similar analysis of the Ulysses SWOOPS plasma data is provided in *Goldstein et al.*, 1995b, but does not include the more recent high latitude data). The Ulysses data were divided into two sets: a) low latitude data obtained outbound from the Earth at radial distances to 4 AU, and b) rotations with average heliographic latitude greater than 40", The adiabatic invariant $T/n^{2/3}$ was computed to determine whether the solar wind was being heated with increasing radial distance. Our results are shown in Figure 3, superimposed with those of *Tu* (1987) which show Pioneer 10 and 11 in-ecliptic data (*Bavassano* and *Smith*, 1986) along with a linear fit to the Pioneer data of *Tu*. The low latitude Ulysses results are somewhat scattered, and agree qualitatively with the Pioneer results which are also variable. *Liu et al.* (1 995) (not shown) have also analyzed in-ecliptic proton and alpha-particle temperature gradients using Ulysses SWICS (ion mass spectrometer) data, and find that in the slow solar wind ions expand adiabatically whereas in the high speed solar wind non-adiabatic heating is significant. The Ulysses SWOOPS results (Fig. 3), not separated by velocity, appear to indicate a slight heating with increasing distance from the Sun, but the rotation to rotation variations are so large that one hesitates to draw a firm conclusion.

The Ulysses high latitude results appear "doable valued" from about 1.5 to 2.5 AU because the data are averaged over solar rotation rather than radial distance; the adiabatic constant at Northern high latitudes was larger than at Southern high latitudes from about 1.5 to 2 AU although this difference vanished beyond about 2,2 AU (this is due primarily to a density asymmetry rather than a temperature asymmetry). It is clear that the high latitude adiabatic invariant measured is much higher than that measured in the ecliptic; this is not surprising as at high latitudes the temperature is higher and density is lower than in the in-ecliptic, slow speed solar wind. Additionally, it can be seen that at high latitudes the adiabatic constant increases most rapidly close to the Sun (from 1.4 to 2.3 AU), and beyond that distance the adiabatic constant is essentially constant, This high latitude result is in apparent contrast with the *Liu et al.* (1995) result that heating in the high speed in-ecliptic solar wind is important from 3 to 5 AU The *Liu et al.* study included all data, whereas our results exclude CMEs and regions that have been shocked. For these reasons, a possible explanation of the contrast between the *Liu et al.* high speed in-ecliptic results and our high latitude results is that shock heating is important in the ecliptic beyond 1 AU; it would not be important at high latitudes during solar minimum because very few shocks would be expected. An alternative explanation of the apparent differences between heating of high speed streams in the ecliptic and at high latitudes would be [hat because MHD turbulence may evolve more rapidly in the presence of velocity shears, wave energy is converted to thermal energy more rapidly in the ecliptic than at high latitudes, Further studies will be required to sort out what is really happening. The dependencies of ion heating estimates upon data selection criteria need to be more thoroughly investigated and documented, Also, it should be possible to observationally study the evolution of the Alfvén wave turbulence as a function of distance from the Sun, and determine how well the energy loss from the turbulence agrees with both the observed ion heating and with predictions from turbulence theory as to the heating rate,

Large-scale Electron Dynamics

A good deal of debate over the large-scale properties of the electron distribution took place at Solar Wind Eight, and it is clear that some basic problems remain unsolved. Even if scattering of electrons by waves is ignored, the properties of the electron distribution with distance from the Sun are difficult to estimate because the electron mean free path for Coulomb collision depends upon electron energy and can be less than or greater than the solar wind expansion scale length. In the hotter portions of the electron distribution that are collisionless, freely moving electrons run away to form a strahl, but how the strahl merges into the collisional thermal electron distribution is at present unquantified. *Scudder and Olbert (1979)* demonstrated that if only a few percent of the electrons are collisionless, the conventional theory for heat conduction in a collisional plasma fails, *Olbert* (1983) later applied a Krook's approximation (a relaxation time method, which is less rigorous than solving the Fokker-Planck equation) to solving the coupled electron distribution function and solar wind equations. *Shoub* (1987) argued that limitations in Olbert's method made

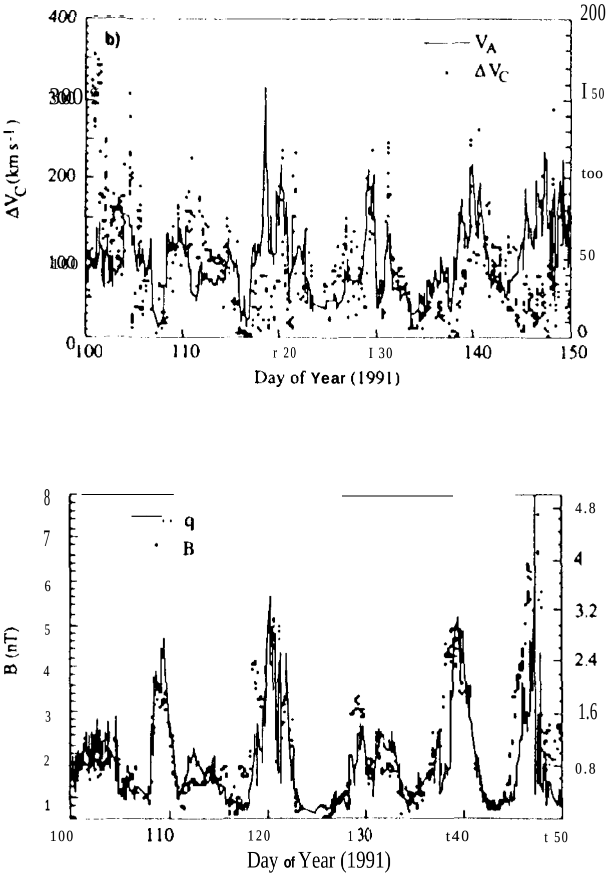

Figure 4. From *Scime et al.* (1994) using Ulysses thermal electron data. The upper panel displays the core electron speed in the plasma frame plotted as dots and the Alfvén speed as a line, both in km/s. The lower panel displays heat flux ($\mu W/m^2$) and the magnitude of the magnetic field (nT).

the results unreliable, and discussed possible improved approaches, but to date a trustworthy calculation is not available,

It may be, however, that the solar wind heat flux is limited by kinetic instabilities, and the basic properties of the electron distribution can be estimated with crude assumptions based upon limiting the heat flux. *Feldman et al.* (1976) investigated the correlation of the heat flux with local solar wind parameters, and found a good correlation with the Alfvén speed. This encouraged models based on the idea that the heat flux is limited by an instability. *Scime et al.* (1994) and *Gary et al.* (1994) have recently investigated these possibilities observationally and theoretically. Scime *et al.* investigated the correlation between the core electron/proton velocity difference and the solar wind Alfvén speed, and between the heat flux and the magnetic field magnitude (Fig. 4). Although at times the Alfvén speed and core velocity difference are well correlated, this is often not the case, On the other hand, the heat flux is well correlated with magnetic field, *Scime et al.* note that if heat flux is conserved along a flux tube, one naturally obtains a correlation between the magnetic field and the heat flux that has nothing to do with heat flux limitation, and note that apparent correlations with solar wind parameters can therefore be misleading.

Gary et al. (1994) adopt a bi-Maxwellian model of the electron distribution, assuming a high density cold beam moving with less than solar wind velocity, and a low density hot beam moving quickly outwards. Unstable modes considered include the magnetosonic heat flux instability, the Alfvén heat flux instability, and the whistler heat flux instability. They conclude that the whistler heat flux instability is easiest to excite, and derive a number of expressions for the instability threshold. Using solar wind parameters based upon Ulysses in-ecliptic plasma conditions, and assuming a minimum growth rate needed for an instability to occur, they derive an upper bound for the global heat flux law (threshold of whistler instability) of:

$$q_e = \frac{40.7}{R^{3.0}} \frac{\mu W}{m^2}$$

Scime et al. compared measured radial heat flux profiles with predictions based on *Gary et al.*, predictions based on a bi-Maxwellian empirical heat flux (*Feldman et al.*, 1975), and with predictions from two models based on collisional heat fluxes. The models based on ad-hoc bi-Maxwellian techniques did well, suggesting that this is a useful way to understand some properties of the solar wind electron distribution, *Scime et al.* observed a power law dependence of:

$$q_e = \frac{10.5}{R^{3.0}} \frac{\mu W}{m^2},$$

Scime et al. note that if the parallel to perpendicular halo temperature assumed by *Gary et al.* is arbitrarily increased from 0.735 (observed value) to 0.95, an excellent quantitative agreement of theory with the observations can be obtained, If we are to use and improve such models, it is necessary to understand if the parts of these models (i.e., core and halo) behave as we might ordinarily expect,

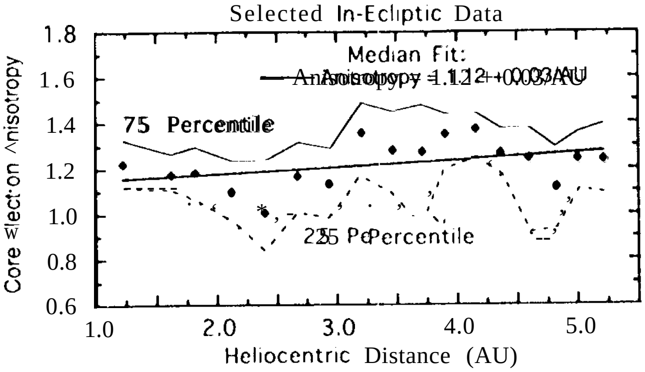

Figure 5. Increase of the core electron temperature anisotropy, $T_\parallel/T_\perp$, with distance from the using Ulysses in-ecliptic data, from *Phillips et al.*, 1995a.

A surprising property of the Ulysses core electron observations beyond 1 AU was the increase with radial distance of the ratio $T_\parallel/T_\perp$ (Figure 5, from *Phillips et al.*, 1995a). Phillips *et* al. , assuming a linear variation of anisotropy with distance from the Sun, find that the anisotropy increases from about 1.15 near 1 AU to about 1.27 near 5 AU. This is not what is expected from conservation of the double adiabatic invariant. *Phillips and Gosling (1990)* find that, in a model for the core distribution based on the double adiabatic hypothesis, $T_\parallel/T_\perp$ should decrease. The cause of the increase of $T_\parallel/T_\perp$ from 1 to 5 AU is unclear. One possibility is that nonlocal collisionless electrons dynamics are important, (e. g., *Scudder and Olbert*). Another idea is that collisional drag of the protons on the core electrons (with the proton drag force on the electrons being balanced by the parallel component of the solar wind electric field) would scatter core electrons, but one would think that such scattering would either isotropize particles or perhaps favor perpendicular heating. Yet another thought is that electrostatic fluctuations (perhaps obliquely propagating whistlers) preferentially heat the parallel component of electron temperature. It is clear that we have a long way to go in understanding solar wind electron dynamics.

Electrons, Mirroring, and Shocks

Electrons, because of their high thermal speeds, may provide information as to processes occurring remote from the point of observation; several interesting examples of such behavior have recently been reported, *Phillips et al. (1992)* have observed (Fig. 6) within a Coronal Mass Ejection not only the usual bidirectional streaming, but an additional unidirectional narrower beam; they named this configuration a "strahl-on-strahl" distribution. Their interpretation is that the broader bidirectional beam is due to electrons that are either mirrored within the CME or have made multiple passes through the CME (presumably being mirrored closer to the Sun). The narrow unidirectional beam is interpreted as coming directly from the Sun without scattering.

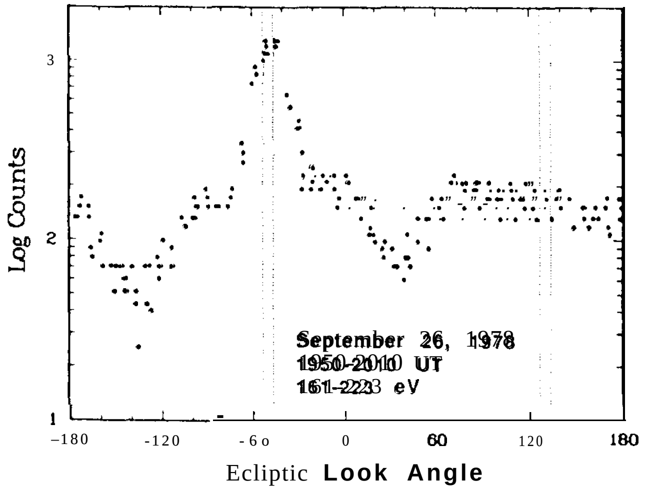

Figure *6.* Strahl-on-strahl distribution from *Phillips et al.* (1992). Log of electron counting rate is shown as a function of in-ecliptic look angle.

Another new class of suprathermal events has very recently been reported by *Phillips et al. (* 1995b). At low solar latitudes and distances beyond *3.37* AU, suprathermal distributions were observed comprising an antisunward field aligned beam, along with a return (sunward) population having a drop out for pitch angles less than 60”. ‘f ’he interpretation is that the sunward moving electrons mirrored from increases in magnetic field occurring farther from the Sun than the spacecraft, and that the wide loss cones are caused by a weak mirror ratio.

And yet another surprise was the discovery of bidirectional str-taming in solar wind electrons not associated with the presence of a Coronal Mass Ejection. *Gosling et al. (1993)* report enhanced fluxes of suprathermal electrons upstream of corotating shocks beyond -2 AU. The events are most intense close to [he shocks, with the typical duration near 5 AU being about 2.4 days, As the upstream sides of corotating shocks face towards the Sun, the electrons leaking from the shock front travel upstream in a direction opposite to the usual solar wind electron heat flux. A significant aspect of this phenomenon proposed by *Gosling et al.* is that scattered suprathermal electrons traveling upstream to 1 AU may contribute to the solar wind halo observed at all pitch angles there.

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