VERY HOT PLASMAS IN THE SOLAR SYSTEM

W.I. Axford
Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau 3,
Germany

INTRODUCTION

In contrast to most astrophysical situations where information about hot plasmas can be obtained only from emission and absorption spectra, often without spatial resolution, plasmas in the solar system in many cases provide us with the opportunity to make direct, in situ measurements. Such plasmas, notably the solar wind and the plasmas contained in the magnetosphere of the earth, Jupiter, and other planets, must be heated by processes which are in many cases similar to those occurring in astrophysical plasmas and their behaviour should also be to some extent similar. It is therefore interesting and instructive to be able to compare our observations and understanding of these accessible solar system plasmas with those found elsewhere in the universe which are not so easy to observe in detail. This might provide us with some new ideas and perspectives on the nature and behaviour of hot plasmas in general and also an opportunity to test some of our ideas against "ground truth".

THE INTERPLANETARY PLASMA

Since the early theoretical work of Biermann and the first in situ measurements by Gringauz and his colleagues there has been a steady development in our knowledge and understanding of the solar wind (see the proceedings of the four 'Asilomar' meetings). Prior to about 1972 the typical solar wind properties at 1 au were considered to be those shown in the first two columns of Table 1. The cause of the solar wind was assumed to be some form of extended coronal heating in combination with heat conduction in the electron component.

There have been a number of developments in recent years, however, which show that the situation is probably much more complex. The most crucial observations concern the existence of long-lived high speed streams which are especially prevalent near the ecliptic plane during periods of relatively low solar activity. Interplanetary scintillation

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observations have shown that at such times the solar wind at high latitudes (> 40°) often has a uniformly high speed which is consistent with the existence of polar coronal holes at such times.

TABLE 1

Energy	Base of corona	Slow stream	Fast stream
Gravitational ($-GM_{\odot}m/r$)	-2000 eV	-	-
Thermal ($\frac{5}{2}K(T_p+T_e)$)	430 eV	30 eV	60 eV
Kinetic ($\frac{1}{2}mV^2$)	-	1000 eV	4000 eV
Total(a)	-1570 eV	+1030 eV(b)	+4060 eV(b)

(a) Average solar wind energy flux ~ 8×10^5 erg $cm^{-2} sec^{-1}$ which is about the same as the transition zone UV radiation flux.

(b) The plasma must be given 2600-5630 eV/e-p pair in addition to the energy it has at the base of the hot corona (~1.5×10^6K).

It has been shown recently that such high speed streams have the property of being very homogeneous in terms of number density, temperature, and, most importantly, the helium to hydrogen ratio (~0.05). In contrast, in what had previously been considered to be the "typical" solar wind, the number density and temperature may fluctuate quite rapidly (by a factor of 2-5, or so) and the helium to hydrogen ratio may vary erratically and rapidly by a very large amount (0.001-0.1). These results suggest that the high speed streams, which at first were thought to be something special, should be considered as really being the "typical" solar wind associated with quiet, steady, magnetically open coronal conditions, whereas the low speed solar wind observed commonly near the earth must have a different and probably more complex origin.

The properties of high speed streams are also summarized in Table 1 and with these one may construct simple energy budgets for the two types of solar wind as shown in Table 2. It is evident that in high speed streams the solar wind plasma must be given some 5-6 keV per electron-ion pair, in addition to the thermal energy of ~ 500 eV per electron-ion pair which exists in a corona with a temperature of ~ 1.5×10^6K. It is evident from this Table that the coronal plasma is gravitationally bound in the simple sense, since the total energy per electron-ion pair at the base of the corona is negative. This implies that heat conduction or an additional energy source is required to allow the coronal plasma to escape from the sun in the form of the solar wind. In fact, heat conduction must be important in such a low density plasma, and since the corona must in any case be heated as a result of the dissipation of the hydromagnetic waves in some form to give it its observed high temperature (above that of the underlying chromosphere and photosphere) it would not be at all surprising if some more extensive heating of the outer corona were to occur.

TABLE 2

Physical properties of the high and low speed solar wind streams

	Slow speed streams	High speed streams
Velocity (V)	< 400 km $\sec^{-1}$	~ 750 km $\sec^{-1}$
Number density (n)	$\sim$ 10-20 cm^{-3}	~ 4 cm^{-3}
Proton temperature (T_p)	$\sim 2x10^4 - 10^5 K$	$\sim 2x10^5 K$
He^{++}/H^+ ratio	$\sim 10^{-3}-10^{-1}$ (highly variable)	~ 0.05 (very uniform)
Origin	possibly emanate from regions of the corona which are 'open' only transiently	apparently associate with regions which are magnetically open for long periods (coronal holes)

Simple theoretical models of the solar wind can explain the gross features of the phenomenon but there are several types of model which are clearly inadequate. For example, an exospheric model in which a collisionless plasma exists above a few solar radii cannot produce the very high speeds which exist in high speed streams and the large ratio of parallel to perpendicular temperatures predicted are also contradicted by observations. Models in which heat conduction is a dominant factor tend to give speeds which are too small (i.e. $\lesssim 400$ km/sec), proton temperatures which are too small, and electron temperatures and heat fluxes which are far too large. It seems clear that heat conduction is an important effect but it is not of prime importance and indeed appears to be to some extent supressed by microscopic instabilities. Simple adiabatic models in which there is no heat addition beyond the base of the corona fail since, as mentioned above, the corona is gravitationally bound to the sun. One can correct the situation by adding a source of heat and momentum to the model, representing the effects on the flow of hydromagnetic waves emitted by the sun. On energetic grounds there is no problem with such a procedure since large amplitude ($\delta B/B \approx 1$) waves are observed everywhere in the solar wind, especially in high speed streams. If one were to extrapolate from 1 au back to the sun using the WKB method, the energy in the waves would be found to be adequate, but since the large amplitudes persist in as close as 0.3 au (i.e. the perihelion distance on the Helios spacecraft) it seems that non-linear effects are limiting the amplitudes of the waves and there is nothing to indicate that this does not happen even as close to the sun as a few solar radii. There is therefore no serious limitation on the wave energy flux available.

Simply to supply the energy of the solar wind is not the only problem, however. There are several remarkable features of the observations which are at the present time only partially understood and which seem to be a clue to the basic heating and accelerating mechanisms. First, the proton temperature distribution tends to have the perpendicular temperature greater than the parallel temperature, especially in high speed streams. This is completely at variance with what would be expected from collisionless and/or purely adiabatic effects. In cool low speed streams Coulomb collisions can in principle be sufficiently important to make the temperature anisotropy small, but they cannot reverse the sense so that we must conclude that some form of wave interaction is required, perhaps cyclotron heating. Second, the behaviour of minor (i.e. heavier) species in the solar wind is remarkable in that they tend to have bulk speeds which are faster than the protons by an amount which can be approximately as large as the Alfvén speed. Furthermore, the temperatures of these minor species are often, especially in high speed streams, much higher than those of the protons and in many cases seem to be such that each species has a temperature proportional to its atomic mass (i.e. the same thermal speed). It seems possible to understand these effects only on the basis of wave interaction effects, with cyclotron resonances being a very likely candidate since among other things it is possible for some differences between species to occur as a result of resonance with the different parts in the wave spectrum.

A basic question is the origin of the relatively high frequency waves required to produce these rather striking effects. Almost all waves other than Alfvén waves tend to be rapidly damped in the interplanetary medium, so that they cannot be emitted directly from the sun. Furthermore, since the Alfvén waves are all propagating away from the sun in regions of uniform flow, a simple wave-wave interaction is not to be expected. Perhaps it is sufficient if Alfvén waves propagating outwards, and therefore becoming eventually non-linear, can decay into a high frequency wave and another Alfvén wave. This could be the process which controls the amplitude of the Alfvén waves beyond a few solar radii and also produces in situ waves which rapidly damp and therefore heat the protons and other species. The Alfvén waves themselves must have an important effect on the flow of the solar wind plasma, but in view of the above arguments the indirect effect associated with the non-linear decay must be more important.

Finally, we must understand why the commonly observed "slow" solar wind is qualitatively and quantitatively different from the rather uniform and steady high speed streams. A possible explanation is that the high speed streams are emitted from regions of the corona which are magnetically open for long periods and, as a consequence, associated with coronal holes. The low speed wind, on this basis, would have to come from regions of the corona which are normally magnetically closed but which open transiently as a result of magnetic field line reconnection induced by motions in the lower atmosphere of the sun and thereby release plasma into interplanetary space. Since the plasma on closed field lines is to a first approximation stationary, it has the possibility to change its composition by gravitational settling, for example. Thus if the plasma is suddenly released it may well have quite a different composition and thermal properties which are quite different from coronal hole plasma which is accelerated right from the base of the corona.

THE MAGNETOSPHERE OF THE EARTH

The earth's magnetosphere contains plasmas displaying a wide variety of characteristics ranging from relatively cool (1-10 eV), dense (10^3-10^4cm^{-3}) plasmas which originate in the ionosphere to hot (10-100 keV), low density (10^{-2}-1 cm^{-3}) plasmas which largely originate in the solar wind. In addition, there are high energy particle populations (0.1-10^2 MeV) which are energetically of minor importance but which are easily measured and give rise to the so-called inner and outer radiation belts detected by early US and Soviet spacecraft.

The main source and the cause of energization of the hot plasma in the earth's magnetosphere is the interaction with the solar wind plasma and magnetic field. As a consequence of stresses exerted at the interface between the solar wind and the magnetosphere (the "magnetopause") a long comet-like magnetospheric tail is formed which, as a result of periodic disruptions ("substorms"), causes captured solar wind plasma to be energized and injected deep into the inner magnetosphere. This last process, which is associated with auroral activity, produces magnetically trapped plasma which spreads around the earth and causes the magnetic field to expand slightly, resulting in the "ring current" effect.

The most important energization processes occurring in the magnetosphere are as follows:

1.) Front side reconnection - As a result of magnetic reconnection between the interplanetary magnetic field and the geomagnetic field, geomagnetic field lines become magnetically "open", allowing trapped energetic particles to escape and solar wind plasma to enter the magnetosphere. In addition, low energy solar and galactic cosmic rays are thus permitted to have direct access to latitudes > 70-75°. The reconnection process also permits Maxwell shear stresses to be exerted on the magnetopause which, perhaps aided by viscous-like effects, gives rise to the formation of the magnetospheric tail.

2.) Tail reconnection - Reconnection (in this case closure) of open magnetic field lines in the tail of the magnetosphere appears to take place in two modes, one relatively steady and slow, and the other sporadic and rapid, occurring in conjunction with substorms. The latter effect appears to be closely analogous to a solar flare and, indeed, many phenomena associated with solar flares have their counterparts in auroral magnetospheric substorms. An interesting feature of these intense reconnection events is that acceleration of electrons and ions to high energies (~ 1 MeV) takes place in the vicinity of the X-type neutral point which is formed as a part of the reconnection process.

3.) Adiabatic motions ("convection") - are associated with large scale electric fields and plasma drifts in the magnetosphere. The electric fields are produced in part as a result of tidal motions in the atmosphere and, more importantly, as a consequence of reconnection in the tail of the magnetosphere which requires that magnetic flux be recirculated to the upstream side of the magnetosphere where it can again become connected to the interplanetary field as result of dayside reconnection. The E.M.F. is typically of the order of 10-100 kV and consequently a plasma with a temperature corresponding to particle energies of the order of 10-100 keV is produced. The mechanism is more or less adiabatic and reversable, so that both energy gains and losses occur. It may be regarded as compression and expansion which occur as the plasma on a given magnetic flux tube moves inwards or outwards from the earth.

4.) Radial diffusion - Random convection, occurring with characteristic time scales which are the order of the time taken for a particle to drift round the earth as a result of the magnetic field gradient curvature effects, can give rise to the spatial diffusion of the more energetic particles. Particles which move inwards continually gain energy, since they tend to conserve their first and second adiabatic invariants. There is nothing to prevent at least a few particles reaching very high energies by this process. The highest energy magnetospheric particles which form most of the inner radiation belt are believed to be produced in this manner, although there may also be some contribution from the decay of cosmic ray produced neutrons.

5.) Parallel electric fields - can occur in situations where strong electric currents produced in the magnetosphere close through the ionosphere and are therefore required to flow parallel to magnetic field lines. This is simply another way of saying that magnetospheric stresses are communicated to the ionosphere which tries to resist the plasma motions and field distortions that would otherwise arise. If the current is so strong that the relative drift speed between electrons and ions exceeds a critical value (certainly not greater than the electron thermal speed and perhaps as small as the ion thermal speed) an instability can occur in which intense turbulence develops or possibly a new plasma distribution is set up (i.e. a "double layer"). In either case, electric fields parallel to the magnetic field tend to arise, causing some electrons and ions to be accelerated in opposite directions. More or less mono-energetic beams of electrons have been observed in association with aurora and appear to confirm that such an acceleration has occurred. The potential drops involved seem to be typically of the order of 1-10 kV (i.e. about 1/10 of the convection E.M.F.). The evidence regarding ions is less clear at present since, although singly ionized helium and oxygen ions which are obviously of ionospheric origin have been observed moving parallel to the magnetic field in the magnetosphere, in situ measurements in the acceleration region have shown that in many cases the energization is due to strong ion cyclotron turbulence.

The main sources of plasma in the magnetosphere are the solar wind and the ionosphere and these have a particular signature in terms of the relative abundances of elements and isotopes and their charge states. Other sources, such as solar and galactic cosmic rays and the interstellar gas, are all relatively unimportant. Both major sources can supply electrons, protons and helium, oxygen and nitrogen ions with roughly similar relative abundances. The most important distinctions between the two sources are the charge states of the ions, which in the case of the solar wind correspond to those of the corona (i.e. He^{+2}, O^{+6}, C^{+5}, N^{+5}, Fe^{+16}, etc.), whereas the ionsophere is largely the result of photoionization of the upper atmosphere by solar ultraviolet light and produces mostly singly ionized ions with the exception of a small amount of O^{+2}. Other clear signatures are the helium isotopic ratio ($\sim 3\times10^{-4}$ in the solar wind and $\sim 10^{-6}$ in the ionosphere), the deuterium to hydrogen ratio (0 and $\sim10^{-5}$, respectively) and the carbon to oxygen ratio (since the abundance of carbon in the atmosphere is very small, indeed). To date, the main evidence for existence of ionospheric ions in the magnetosphere involves the detection of singly ionized helium and oxygen ions. The presence of solar wind ions is evidenced through measurements of doubly ionized helium in the aurora, a carbon to oxygen ratio of the order of unity among relatively high energy particles and, also in the aurora, a helium isotopic ratio approximately equal to the solar value. The present indications are that, on a total energy basis, the hot plasma in the earth's magnetosphere is ~ 90% solar and ~ 10% terrestrial. However, this ratio could vary with time and also with location in the magnetosphere.

THE MAGNETOSPHERES OF OTHER PLANETS

It is known definitely that Mercury, Jupiter, and Saturn have magnetospheres with associated hot plasmas and/or energetic particle populations. Mars and Venus may have magnetic fields but if so they are too weak to allow significant magnetospheres to form and there is little evidence for very hot plasmas and particle energization to be found in the data available at present. Uranus and Neptune may have substantial magnetospheres but there is only weak evidence based on reports of low frequency radio emissions from Uranus.

The Jovian magnetosphere has been investigated by four spacecraft (Pioneer 10/11 and Voyager 1/2) and it has been found to have some remarkable properties. The essential features of the magnetosphere are that it is dominated by rotation forces as a result of its large size and the rapid rotation of the planet and also that it contains four major satellites, one of which (Io) has a thin atmosphere of SO_2 and is a copious source of plasma. Undoubtedly all the processes described above as occurring in the earth's magnetosphere also occur at Jupiter, however the additional effects of rotation and the Io plasma source appear to be equally important if not dominant.

The Jovian plasma is sufficiently dense to be observable from its visible and UV emissions, the lines which have been identified include those of S II-IV and O II-III. In situ plasma composition measurements have confirmed the presence of these ions and in addition SO_2^+, Na^+, and protons. Energetic particle composition measurements (energies exceeding about 100 keV/nucleon) have detected sulphur, oxygen, and sodium ions and in addition have shown that there is a small component of carbon and helium which is evidently of solar origin, since it is most prevalent in the outer magnetosphere. The proton to alpha-particle ratio is surprisingly rather large (100-300) and variable, suggesting that another source is supplying protons, namely the Jovian ionosphere.

While processes such as magnetic field line reconnection, convection, radial diffusion, and electric fields parallel to the magnetic field lines must all play a role in accelerating particles in the Jovian magnetosphere, there are two very important effects which do not occur in the case of the earth's magnetosphere, namely rotation and ion pick up. Since the corotational speeds in the Jovian magnetosphere are of the order of 100-1000 km/sec, it is evident that particles which are injected in the inner parts of the magnetosphere can achieve rather large energies on moving outwards, especially if they are sulphur or oxygen ions. This does not immediately produce a hot plasma, but if the rotational motion is eventually interrupted by stretching and reconnection of the magnetic field lines, for example, the directed kinetic energy can be converted to thermal energy and a hot plasma can be the result. The pick up of a freshly produced ion by magnetic field lines moving relative to a neutral gas provides an interesting acceleration mechanism which has been discussed extensively in the case of the interaction of the solar wind with comets, the interstellar medium, and thin planetary atmospheres. The essential point is that the new ion can only make a circular motion in the frame of the moving magnetic field lines and plasma, preserving its speed, so that the relative speed becomes the speed of "thermal" motion. By this process ions produced in the vicinity of Io, for example, are immediately given thermal speeds of the order of 60 km/sec which corresponds to 400 eV, 800 eV, and 1.6 keV for oxygen, sulphur, and sulphur-dioxide ions, respectively. Thus it is possible to generate a very hot plasma purely as a result of ionization. This appears to be a very important source of heating for the Io-associated plasma as it is sufficient to account for all the additional ionization and radiation due to inelastic collisions which is observed.

A close passage through the magnetosphere of Saturn is to be made by the spacecraft Pioneer 11 in September 1979. Provided the magnetic field strength is sufficiently large, we expect a situation rather more similar to that of Jupiter than the earth, namely with rotation playing a dominant role and a source of plasma, this time Titan, in the inner magnetosphere. There is an essential difference, however, in that the atmosphere of Titan is evidently thick and primeval, in contrast to the atmosphere of Io which is thin and continually replenished by venting of volatile material from beneath the crust. One certainly does not expect to detect sulphur ions in the magnetospheric plasma in this case but, depending on the composition of the atmosphere of Titan, carbon, nitrogen, and oxygen are likely to be prevalent. At Uranus, a somewhat different situation prevails, since in this case the axis of rotation of the planet lies in the ecliptic plane and at the present time the solar wind blows directly onto one of the polar regions on the planet. There is no expectation of a satellite having an atmosphere and since the composition of the ionosphere is not the same as that of Jupiter and Saturn, one should also expect therefore that the magnetosphere has quite different properties.

CONCLUSIONS

A great deal of understanding of the origin and behaviour of the very hot plasmas which exist in the solar system has been achieved during the 20 years in which in situ measurements have been possible. In retrospect, perhaps the biggest surprises have been the diverse nature of these plasmas and the wide range of processes which heat them and cause some particles to be accelerated to very high energies. These processes must surely also be important in more general astrophysical contexts and they deserve deeper study for that reason alone. However, before rushing off to apply what we have learnt one should perhaps also remember that one of the most salutary results of space plasma physics has been that our initial simple theories were almost always wrong and that nature has a perverse and subtle streak which permits things to happen which one might never have expected.