O\textsuperscript{5+} ACCELERATION BY TURBULENCE IN POLAR CORONAL HOLES

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ABSTRACT

Recent Observations by the Ultraviolet Coronal Spectrometer (UVCS) Instrument onboard The Solar and Heliospheric Observatory (SOHO) have revealed highly anisotropic distributions of O\textsuperscript{5+} ion velocities, notably that the very broad spectral lines suggest a large speed along the line of sight, an order of magnitude higher than what would be expected for a plasma in local thermodynamic equilibrium at the inferred electron temperature. In this paper we investigate a possible microscopic acceleration process for ions in the solar wind.

Key words: solar physics; solar wind; particle acceleration.

1. INTRODUCTION

The UVCS instrument on board SOHO makes observations of the solar wind above the limb of the sun from 1.5 to approximately 12 solar radii. It is designed to observe principally two spectral lines - the Lyman \( \alpha \) line at 1216\AA and the Oxygen VI Doublet at 1032, 1037.6 \AA. The design specifications (Kohl \textit{et al.} 1995) were to be able to resolve half-widths of a few tenths of an Angstrom, as was expected for the gas in thermal equilibrium at a temperature of \( 1 - 3 \times 10^8 \text{K} \). The first results from the instrument however indicate line widths in the oxygen doublet which are much broader. At 1.5R\( \odot \), Kohl \textit{et al.} find line widths corresponding to a line-of-sight velocity of \( 100\text{km/s} \) - an O\textsuperscript{5+} L.O.S. kinetic temperature of \( 10^7\text{K} \), rising to \( 350 - 500 \text{km/s} \), at 2.1 R\( \odot \), corresponding to a kinetic temperature of a few times \( 10^8\text{K} \). The situation is patently very different from what was expected at the outset.

The particle speeds perpendicular to the line-of-sight are also accessible with UVCS, and preceding instruments working on the same principle. Using the Doppler dimming technique (eg, Noci \textit{et al.} 1987, Strachan \textit{et al.} 1993) neutral hydrogen speeds of 153 - 251 km/s at 2R\( \odot \) have previously been inferred, (Strachan \textit{et al.} 1993) whilst for OVI atoms the inferred velocities range between \( < 150 \text{km/s} \) at 1.5R\( \odot \) and 100-125 km/s at 2R\( \odot \) to 130-230 km/s at 3R\( \odot \) (Kohl \textit{et al.} 1997). Close to the solar surface the direction perpendicular to the line-of-sight is almost the same as the field direction, whilst that parallel to the line-of-sight is almost perpendicular to the field region. So at first sight there appears to be a perpendicular anisotropy in the O\textsuperscript{5+} ion distribution.

Comparing between the O\textsuperscript{5+} and the neutral hydrogen velocities (neutral hydrogen in the solar wind almost maps its ionised counterpart, cf Allen \textit{et al.} 1996) it is found that the kinetic energy per atomic mass unit is higher for the O\textsuperscript{5+} ions than it is for the neutral hydrogens, suggesting that there may be a resonant process, preferentially accelerating the higher mass atoms.

An anisotropy in the O\textsuperscript{5+} distribution could potentially be generated through ion acceleration by plasma waves with a large component perpendicular to the magnetic field. A resonant wave acceleration mechanism could, moreover, allow the selection of ions on the basis of their charge to mass ratio, as resonant plasma processes tend to work on the basis of a matching between some local frequency and a particle gyrofrequency. Previous work by MacKenzie, Banaszkiewicz and Axford (1993) on the acceleration of the high speed solar wind in general has invoked as a driver for the wind high frequency (up to 10kHz) waves propagating out along the open field lines. Axford and MacKenzie (1991) suggested that an appropriate energy source of these waves would be in the microflaring activity of the coronal base.

In this paper we will investigate the trajectories of test O\textsuperscript{5+} ions and protons in the field of two types of high frequency waves, and assess the potential for acceleration of solar wind ions by a turbulent or resonant means.

The philosophy of this work is simple. We take a plasma wave spectrum of a nature acceptable given observational and theoretical constraints, and we place in these waves ions of particular charge-to-mass ratio, and calculate their trajectories as test particles in an oscillating electromagnetic field, by solving the equations of motion for the ion in the field of the waves. (The fact that they are test particles means that they have no consequence for the distribution of waves which accelerate them). The evolution of single particle parameters is studied, as well as that of distributions.
2. SOURCES OF PLASMA TURBULENCE

The ions of interest are accelerated by 'high frequency' turbulence. By 'high frequency' we here mean turbulence at a frequency comparable to the gyrofrequency of the particles of interest, i.e., \( \nu_1 \sim 9.6 \times 10^3 BZ / M \) s\(^{-1} \), where \( B \) is the local magnetic field (Gauss), and \( Z/M \) is the ionic charge-to-mass ratio. For \( O^{\pm} \) ions in a local field \( B \) of 10G, \( \nu_1 \approx 30 \) kHz. For \( H^{\pm} \) ions, \( \nu_1 \approx 90 \) kHz, so considerably higher.

Axford and MacKenzie (1991) suggested that the driver and heater for the fast solar wind streams could be the small-scale impulsive reconnection events occurring in the supergranular network boundaries, which liberates the convective energy of the sub-photospheric layers on a small scale, in high-frequency turbulence. In the closed field regions of the 'quiet sun' they hypothesised that this is trapped and converted to localised heating, whereas on the open field regions it drives and heats the fast wind. Their proposition is further that the value of the energy flux transferred to the corona is the same at all positions, only the manner in which is dissipated leads to the different phenomena of fast solar wind from the poles versus heating and slow (thermal) solar wind from the equator.

The frequency of the waves generated in reconnection events is fairly high - distortions of the field on the scale of \( < 10^6 \) cm for microfilament events, propagating at the local Alfvén speed (\( \sim 10^9 \) cm s\(^{-1} \)) for \( B = 1000 \) G, \( n_e = 5 \times 10^8 \) cm\(^{-3} \) gives periods of \( \leq 0.1 \) s and we could reasonably expect a spectrum of turbulence corresponding to smaller (unresolvable) lengthscales to be present. Indeed, if the reconnection energy scales as the square of the dimension of the event, then observed distributions of reconnection events, which favour small energy events (eg. Crosby et al. 1991), also speak in favour of a distribution of wave lengthscales which increases with decreasing lengthscales (increasing timescales). Waves may also be driven by some other process, as in the second case we study, where a low energy electron beam accelerated in a reconnection event forms a source of free energy for the driving of waves via the two-stream instability.

3. STOCHASTIC GYRORESONANT ACCELERATION

Ions in plasma disturbances in a magnetised plasma pick up energy through resonant processes if the matching condition

\[
\omega_i - s \Omega_w - k v \cos \alpha \cos \theta = 0
\]  

is satisfied, where \( \omega_i, \Omega_w \) are the ion and wave frequencies respectively, \( s \) is an integer, \( k, \theta \) are the wavenumber and angle of propagation to the magnetic field and \( v, \alpha \) are the particle speed and angle of propagation to the magnetic field. The process of acceleration of a particle in this manner can be viewed as the particle executing a periodic orbit in the potential well of the wave, with its parallel momentum varying by an amount \( \delta p_p \) about the resonant momentum \( p_p \) which satisfies Equation 1. The amount by which it varies is called the trapping width, and can be found by solving the Hamiltonian for the particle in the field of the wave (Karimabadi & Mendluk, 1991). In a continuous or closely-spaced wave spectrum, then the trapping widths of particle resonances may overlap, allowing a particle to move between resonances in a stochastic manner, gaining large amounts of energy in the process. This process has been modelled numerically using test particle simulations by e.g., Miller and Vinas (1992) for the case of preferential acceleration of \(^{3}\)He and Fe in solar flares, and by Karimabadi et al. (1997), for the case of electron cyclotron acceleration in flare loops. We shall take a similar approach in the problem of \( O^{\pm} \) acceleration.

The differential equations describing the evolution of a test-particle in the wave field are

\[
\frac{dP}{dt} = q(v/c \times B_s + \sum_{j=1}^{N} (E_j + v/c \times B_j))
\]

\[
\frac{dx}{dt} = v
\]

where the sum in Eq. 2 is over the particle resonances. We solve Eqs. 2 and 3 using a Runge-Kutta-4 integrator with adaptive steps (courtesy of P.Petkaki), to an accuracy of one part in \( 10^7 \).

In certain instances of wave-particle acceleration when coupled with particle-wave generation (as in the case of the electron-cyclotron maser, with closely-spaced magnetic loops for example) the test particle treatment is not reasonable, however at present we make the assumption that the waves which accelerate the ions are generated by some other means than the ion distributions themselves. Furthermore, we treat the waves as constant drivers and do not calculate the effect on them of the extraction of energy by the test particles, although we do realise that this must at some point be included.

We have chosen two particular types of wave, but it should be noted that the treatment we present here can in principle be applied to any plasma fluctuation.

3.1. Parallel propagating Alfvén waves

On open field lines, the most straightforward type of waves are are parallel propagating Alfvén waves, both right and left-circularly polarized. These waves have electric field vectors perpendicular to the direction of propagation, making them good at accelerating particles perpendicular to the magnetic field lines.

We assume the presence of a continuous distribution of Alfvén waves with energy density \( U(k)dk = U_s k^{-\alpha}dk \). The cutoff in this distribution is at \( k_{\text{min}} = 1/d \) where \( d \) is the typical scale of the reconnection (\( 10^8 \) cm is assumed). The resonances of a particle at with a particular speed and pitch-angle are given by Eq. 1. In the present simulation only the first ten resonances available to a particle are included in the sum, and the power in each wavenumber \( k_i \) is calculated as follows.
The energy density in a wave $k_i$ is given by

$$U_{k_i} = U_E + U_B = \frac{|E_{k_i}|^2}{8\pi} + \frac{|\Delta B_{k_i}|^2}{8\pi}$$

(4)

and the magnetic and electric energy densities in the case of Alfvénic fluctuations are in the ratio

$$\frac{U_E}{U_B} = \frac{\nu_A^2}{c^2}$$

(5)

Thus knowing the dependence of $U_{k_i}$ on $k_i$ we can derive an expression for $E_{k_i}$, i.e.

$$E_i = \frac{(8\pi n - 1)U_{tot} k_i^{-n} dk}{2k_{max}^{-1}((c/n_A)^2 + 1)}$$

(6)

where $U_{tot}$ is the total wave energy density in the corona, equal to the energy flux divided by the Alfvén speed, and $dk_i$ is the assumed width in $k$-space of the resonance, which is a free parameter. We take $U_{tot} = P_{tot}/\nu_A \sim 10^6/\nu_A$ ergs cm$^{-3}$, corresponding to the energy flux deemed necessary to heat the corona. For the time being, we take $dk_i = 0.1k_i$. We use local parameters $\nu_A = 10^6$ and $n_A = 10^8$ cm$^{-3}$. The resonant waves are both right and left-handed, and the chirality is chosen at random for each resonance which a particle experiences. The resonance wavelengths and frequencies, powers and chiralities are calculated anew at each timestep.

We have tested the integration code in a number of simple cases: simple gyromotion in the absence of waves (in which we check for the conservation of energy and the characteristic sinusoidal variation in x-y position), motion in the presence of a single circularly polarized, parallel propagating Alfvén wave (in which a periodic energy gain and loss by the particle is seen) and in the presence of two or more well-separated Alfvén waves of identical chirality (in which case beat phenomena of the appropriate periods are observed). In these simple cases the code performed as expected, making us confident of the reliability of results in the more complex cases.

3.2. The acceleration of $O^{5+}$ atoms

The typical results for case of a single test oxygen atom are shown in Fig 1. The particle trajectory shows an erratic acceleration over a timescale of seconds. The criteria for stochasticity has, however, not been exceeded. According to Karimabadi and Menyuk (1991), the quantity $\epsilon = |q|/E/mc^2$ must be $\sim 1$ for stochastic behaviour to take hold. The erratic path of the oxygen atom is due to the random chirality of the waves with which it interacts. With these parameters, the timescale for acceleration for $4 \times 10^6$ cm$^{-1}$ is of the order of 3 seconds. It can furthermore be seen that the parallel speed of the particle also undergoes an increase, but that it is smaller, gaining speeds only of the order of $2 \times 10^6$ cm$^{-1}$.

This falls into line with the observations of a high perpendicular velocity component, compared to the parallel value.

A single particle trajectory has little meaning, indicating only whether one has periodic or random motions, and whether acceleration is at all possible.

We have repeated the simulation for 500 $O^{5+}$ ions, though over a much shorter timescale and are thus able to construct a particle distribution, which indicates quite clearly that a large proportion of the $O^{5+}$ ions present are accelerated to above their initial energy by the action of the Alfvén waves. Approximately 20% of the injected ions end up with velocities higher than those with which they started ($\sim 1.25 \times 10^6$ cm$^{-1}$), after a few tenths of a second. The energy deposition distance, calculated by multiplying the acceleration time with the parallel speed, is a few hundred kilometers, necessary for the $O^{5+}$ ions to reach the observed high perpendicular speeds.
3.3. The acceleration of protons

The question remains of how the oxygen ions are preferentially accelerated by this process. For this particular choice of input wave spectrum an answer is forthcoming, though we do emphasise that it is conditional on having a spectrum in which the power per unit wavenumber decreases with increasing wavenumber. The cyclotron frequency of protons is higher than that of O$^{5+}$ ions, so with a spectral form \( W(k)dk = W_c k^{-n} \), the power in the wavenumbers at which it resonates is lower than in the resonant wavenumbers for the O$^{5+}$ ions. One would therefore expect that the efficiency of acceleration will be reduced. Simulations show that this is indeed the case, though we do not show the results here. The simulation is run with exactly the same parameters as in the case of O$^{5+}$ ions, except that the ion charge and mass are varied. The simulation is run for the same time. None of the particles in the simulation move out of the first velocity bin during the time of the simulation, indicating a lower rate of acceleration for protons than for O$^{5+}$ ions. As thermal equilibrium is assumed at the start of the simulations, the protons do start off with a higher speed than the oxygen atoms, but they are not accelerated during the simulation.

The general characteristic of acceleration in this way will be, we expect, the preferential energisation of ions with a low charge-to-mass ratio compared to those with where this ratio is high. But we emphasise again that this is due to the form of our input wave spectrum. A spectrum in which the power per unit wave-number increases with increasing wavenumber will result in the opposite effect.

4. Acceleration by Shear Alfven Waves

The problem of the selective acceleration of ions with a particular charge to mass ratio has been investigated by Miller and Viñas (1993) in the context of impulsive solar flares, where the ratio of Fe/C is observed to be substantially increased over its photospheric value. This suggested a resonant acceleration to these authors, who describe a model in which the selectivity is guaranteed because only certain types of waves are present. Such a model is in principle applicable also to the case of polar coronal holes. The model of Miller and Viñas proposes that a reconnection event leads to the generation of a low energy electron beam, which, via a streaming instability (of these non-thermal electrons relative to the background plasma) drives unstable certain types of plasma waves, which then accelerate ions, on the basis of their charge to mass ratio. This is also a plausible chain of events for polar coronal holes if the small brightenings observed in UV, and often found at the foot of polar plumes, are assumed to be microflaring events in which reconnection occurs.

The type of waves driven unstable by the low energy electron beam depend on the nature of the local plasma. The parameters used by Miller and Viñas (1993) are happily also reasonable for a microflaring plasma, relieving us of the necessity to solve the plasma dispersion relation anew (in the present calculations at least). These parameters were a warm background plasma of \( T_e = 10^5 \text{K} \), and \( \sqrt{(n_e + n_i)} = 100 \beta \) where \( n_e, n_i \) are the background and reconnection beam density respectively. If we take a typical brightpoint field of 100G, we see that this implies \( n_e + n_i \approx 10^3 \text{cm}^{-3} \), which is reasonable.

The acceleration in this case is stochastic acceleration in that the waves are closely enough packed and with a large enough amplitude that particles can jump from resonance to resonance, gaining energy in a random fashion as they do so. We use a wave field with parameters found in Miller and Viñas (1993), who found fast-growing shear-Alfven and H$^+$ electromagnetic ion cyclotron waves. The EMIC waves are driven unstable between about 0.6 and 0.85 \( \Omega_p \), whilst the shear Alfvén waves are unstable up to about 0.42\( \Omega_p \). Both can accelerate O$^{5+}$ ions, whose cyclotron frequency is 0.3125\( \Omega_p \). Other wave modes present grow far slower. We use a collection of 1000 shear Alfven waves, \( E_{11} = (E_{11} \cos \psi_i, -E_{11} \sin \psi_i, -E_{11} \cos \psi_i) \), and electric vectors \( E_{11} : E_{12} : E_{13} = 10^2 : 10^{-2} : 1 \). The waves are started with random phases and have frequencies uniformly distributed over 0.3 - 0.42\( \Omega_p \), and wavenumbers between 3000\( \Omega_p/c \) and 4000\( \Omega_p/c \). These are the fastest growing waves in the distribution. They have a single propagation angle to the magnetic field of 88.3°. The energy flux in these waves is assumed to be higher than the mean energy flux input to the corona, but of course the reconnection events generating the beams which accelerate the waves are assumed to have a surface filling factor much less than 1. The total energy density in the 1000 waves we use is 0.045 ergs cm$^{-3}$. The magnetic fluctuation is related to the electric fluctuation by Faraday's law \(-B_t = (\mathbf{k} \times E_i)\), and is therefore many times larger than the electric fluctuation. By assuming that each wave present has the same amount of energy, one can calculate the electric field fluctuation of each wave.

The parameters of the fastest growing waves are such that the gyro-frequency of the O$^{5+}$ ions lies within their frequency band, whereas that of protons lies outwith the frequency band.

The trajectory of a single O$^{5+}$ ion under these conditions is shown in Figure 3. Extrapolating this behaviour to perpendicular speeds of 400km/s gives acceleration timescales of the order of a few tenths of a second.

Apparently the collection of shear Alfvén waves is also capable of accelerating O$^{5+}$ ions, again resulting in a higher perpendicular than parallel speed. There are two important remarks to be made regarding this. The fact that this anisotropy exists is because of the chosen ratios of electric fields in the three directions, which is determined by the nature of the waves which can be generated and grow in the plasma. The fact that O$^{5+}$ and other heavy ions are accelerated rather than protons is again due to the type of waves which propagate. The types of wave are determined by the ambient plasma parameters. As was mentioned above, the parameters for which the analysis of Miller and Viñas can be applied are reasonable for small reconnecting brightpoints as well, but it is really desirable that a study of the types of wave propagating in
Figure 3. The path of a single O^{5+} ion in the field of 1000 shear Alfvén waves.

all reasonable combinations of plasma parameters be carried out, to see if this is a unique case.

This should not detract from the conclusion that, as has been found in solar flares, the acceleration of ions on the basis of their charge-to-mass ratio is possible. It further provides a possible channel for the input of energy into the solar wind from reconnection events, albeit in a small way.

5. Conclusions

Two mechanisms for the selective acceleration of O^{5+} ions have been investigated. In the first case, acceleration by a continuous spectrum of parallel propagating left and right-hand circularly polarised Alfvén waves, the preferential acceleration is accomplished by the nature of the input wave spectrum, in which there is more power in the waves with which ions of low charge-to-mass ratios resonate. It is found that an acceleration of up to 100s of km/s can be accomplished in a few seconds. The perpendicular velocity component is found to be larger than the parallel one. Overall, around 20% of the entire test population is accelerated. A prediction of this model, which could be observationally established, is that other ions whose emission is studied by UVCS should have perpendicular kinetic energies per unit mass ordered by charge-to-mass ratio, with low charge-to-mass ratio ions having the most energy.

In the second case, acceleration is accomplished by a distribution of shear Alfvén waves with parameters determined by the fastest growing modes in the plasma. The acceleration timescale in this case is estimated to be a few tenths of a second. O^{5+} ions are accelerated because their gyrofrequencies lie within the range of frequencies of the fastest-growing modes; proton gyrofrequencies are outwith the frequency bands of any of the fastest growing modes in the plasma, meaning that if acceleration can occur at all it will be far less efficient. In this case there will be no simple relationship between charge-to-mass ratio of an ion and its perpendicular velocity - the distribution will depend on the waves present in the plasma.

REFERENCES


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