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Alfvén waves in the solar corona and solar wind

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Abstract. Alfvén waves have long been known to be a major component of the turbulence measured *in situ* in the interplanetary medium. Until recently, however, observations had been limited to the ecliptic plane, where the solar wind structure is complicated by the interaction of fast and slow solar wind streams, the Alfvénic turbulence being essentially limited to high-speed streams in well defined magnetic sectors. The *Ulysses* spacecraft has shown how this structure disappears with increasing latitude, leading to a relatively constant high-speed ($\simeq$ 750 km s^{-1}) stream originating from polar coronal holes. Within this region the radial magnetic field appears to be relatively constant with latitude, and the fluctuations are everywhere dominated by large-amplitude Alfvén waves propagating away from the sun, covering a broad band of wavelengths. Here we discuss the origin and evolution of solar wind Alfvén waves; the possible role played by such fluctuations in the heating of the corona and acceleration of the high-speed wind is explored in the light of both analytical models and numerical simulations.

1. Introduction

In situ observations in the ecliptic plane have shown that fluctuations in the MHD frequency range, between 10^{-4} Hz and 10^{-2} Hz, present two distinct states: in fast streams originating from coronal holes, the turbulence consists of large-amplitude Alfvén waves propagating away from the sun. This Alfvénic state is also characterized by an almost constant magnetic field amplitude and a very low level of density fluctuations. In the slow solar wind, on the other hand, the turbulence shows features which might deserve the name ‘standard’, in the sense that waves with a definite sense of propagation are difficult to identify and fluctuation spectra follow a Kolmogorov power law. Also, relative density fluctuations follow the Kliatskin scaling $\delta\rho/\rho \simeq \delta u^2/c^2$ where δu is the rms velocity fluctuation and c is the speed of sound (Grappin *et al* 1991). There is evidence that in the ecliptic plane turbulence in the fast streams evolves towards the state typical of slow streams and the main agents in driving this evolution must be related either to the global heliospheric structure, i.e. magnetic field spiral rotation, velocity and magnetic field shears between the streams, the overall solar wind expansion, or to intrinsically compressible non-linear effects. The reason is that incompressible, vortex non-linear interactions in a homogeneous magnetic field results in a process known as dynamical alignment (Dobrowolny *et al* 1980) which leads asymptotically to a state dominated by Alfvén waves propagating in one direction. This state, with a monodirectional spectrum, then represents an exact non-linear solution of the incompressible MHD equations, and is strikingly reminiscent of the state observed *in situ* in the inner heliosphere and in the polar heliospere by *Ulysses*: the observed evolution is, however, away from such a state. Hence, in the regions where *in situ* observations are available, dynamical alignment is not working, and the fluctuations seem to be slowly evolving towards more Kologorov type spectra. The question of the origin of the Alfvén wave spectrum and its evolution in the corona and inner heliosphere therefore remains an open one, and in the following sections we will address some of the processes which could shape this evolution. To begin, we give a summary of the basic observational facts.

2. Observations

The solar wind is a supersonic flow characterized by its large-scale fluctuations (the stream structure) which are also supersonic. Beyond the acceleration region, somewhere within the first tens of solar radii from the photosphere, the flow expands more or less radially; the coronal source regions of the flow rotate with the sun and may be quasi-stationary for several rotations, so that at least within the inner heliosphere the wind bears the imprint of its source structure, though probably deformed by dynamical interaction.

Because of the mean radial expansion, the density ρ falls with heliocentric distance R on average as R^{-2}; the temperature also falls rapidly (the slowest wind streams cooling more or less adiabatically, as $R^{-4/3}$, while the faster streams show a significant amount of heating). As a result, within the satellite-explored regions, the Mach number increases with distance, and the large-scale fluctuations remain supersonic out to large heliocentric distances.

At large scales (1–6 days in the satellite frame of reference), the flow structure is coupled with the magnetic structure, both originating from the solar surface structure. The average speed of the wind increases with heliomagnetic latitude, the large-speed regions extending down much closer to the equator near the solar minimum. Because the solar magnetic equator is inclined (and warped) with respect to the ecliptic, a spacecraft in an in-ecliptic orbit samples slower streams as it crosses the magnetic neutral sheet embedded in the wind. The stream structure is also a temperature structure. In the ecliptic plane, temperature has been observed to correlate well with velocity: high-speed streams are hotter than slow streams. During the solar maximum these hot, fast streams disappear from the spacecraft's data because the fast streams are restricted to higher magnetic latitudes.

From 13 September 1994 to 31 July 1995 the *Ulysses* spacecraft made a rapid northbound transit from -80.2° to 80.2° heliographic latitude, giving for the first time an 'instantaneous' picture of a north–south cut of the heliosphere (heliocentric distances were 2.29 AU and 2.02 AU at peak southerly and northerly latitudes, respectively). *Ulysses* encountered continuous fast wind (in a range from 700 to 800 km s^{-1}) at all latitudes excepting a window extending from -22° to $+21^\circ$ where the stream structure typical of in-ecliptic observations reappeared (Phillips *et al* 1995).

Scales smaller than one day in the solar wind cannot be mapped easily onto well defined solar features, although some authors have associated pressure-balanced structures in the wind with ray-like structures and plumes in coronal holes. In fact, a continuous spectrum of random-like fluctuations ranges from scales of days down to minutes (Coleman 1968). The state of these turbulent scales is not independent from the dynamic and thermodynamic state of the largest scales: one may distinguish several features, depending on whether one considers the turbulence at a fixed heliocentric distance or its global variation with distance.

The variation with stream structure was first noted by Belcher and Davis (1971), who reported that in the 'trailing edges of high-speed streams' one could observe a dramatic reduction in the number of degrees of freedom of the fluctuations, as magnetic and kinetic fluctuations appeared to share the same energy and to be almost perfectly correlated during long periods, with small fluctuations in the density. These 'Alfvénic' fluctuations were generally viewed as large-amplitude waves propagating freely away from the sun. On the other hand, Coleman (1968) considered the fully developed spectra as evidence of MHD turbulence induced by the velocity shear between fast and slow streams. The observations between 0.3 and 1 AU by the Helios mission further showed that the energy spectra evolve with distance, high frequencies decaying with increasing heliocentric distance more rapidly than low frequencies (the decay with distance of the energy per unit mass followed closely the so-called WKB Alfvén wave prediction $E \sim R^{-1}$ at lower frequencies). This observation conclusively demonstrated that non-linear interactions, and not only the linear effect of the expanding wind, must play a role in the evolution of the turbulence.

The *Ulysses* observations in the polar regions have shown some evidence of evolution of the Alfvénic spectra with distance from the sun (Horbury *et al* 1995 a,b, 1996), though it appears that the turbulence is in general much less evolved and is clearly dominated by outwardly propagating waves with a high correlation coefficient ($\geqslant 0.72$) between magnetic field and velocity fluctuations for waves with periods below 10 hours (Smith *et al* 1995, Balogh *et al* 1995). The origin of the (albeit slow) evolution of the turbulence in the absence of large-scale stream shears remains at present somewhat mysterious, though it may perhaps be related to the interaction with the so-called microstreams (Goldstein *et al* 1995) (fluctuations in the radial velocity field with periods of up to two days and amplitudes of 50–100 km s^{-1} (Neugebauer *et al* 1995)), especially since a strong relation between turbulence and stream structure has been observed in the ecliptic involving the ratio b/B of the magnetic fluctuations at the hour scale to the average field. This quantity appears to be remarkably constant and independent of distance; this has been interpreted as indicating the presence of a non-linear ‘saturation’ effect, working to stop the growth of magnetic fluctuations (linear propagation alone would predict that the level of the relative fluctuations should grow with distance within the inner heliosphere).

Outside periods around the solar maximum other parameters characterizing the average state of the plasma also correlate well with the turbulent level, in a frequency range between several hours and a minute. The best indicator has been found to be the average thermal speed of the plasma. The sensitivity of the turbulence level to temperature variation increases with frequency, so that the energy spectrum is flatter in hot, high-speed streams than in cold, slow streams. It is not clear whether these correlations are really indicative of direct interactions between large and small scales or whether they are remnants of solar coronal initial conditions. In any case, the turbulence properties vary continuously between the Alfvénic state noted above and a non-Alfvénic state characterized by larger relative density fluctuations (the relative density is here defined as normalized to the turbulent Mach number squared) and an excess of magnetic relative to kinetic fluctuations. This remains true near the solar maximum, although the relation between turbulence and stream structure almost disappears, together with the stream structure itself, at least in the near-ecliptic region (*Ulysses* will sample the out-of-ecliptic heliosphere close to the solar maximum during its second polar passages).

The solar wind at maximum heliomagnetic activity appears to further present distinct states, characterized not only by the wind speed but also by the mass flux (which at solar minimum is remarkably constant) and hence also by the energy flux. Alfvénic fluctuations are observed both in the high and low energy flux winds, but although the basic correlations with wind speed and temperature remain valid in the high-energy-flux winds, the Alfvénicity does not correlate well with temperature or speed in the low-energy-flux wind.

It is tempting to interpret the non-Alfvénic turbulence found in the cold, slow winds as the ‘standard’ state of relaxed turbulence, towards which the ‘Alfvénic’ one would decay asymptotically: during this evolution, the decrease of the dominance of the outward propagating component occurs simultaneously with the growth of density fluctuations and of magnetic energy excess. The above scenario is supported by the association found between the amplitude of the inward propagating component and the level of density fluctuations (this casts some doubts on the interpretation of the inward propagating amplitude as really representing inward propagating Alfvén waves). However, this picture would seem to be contradicted by simple dimensional estimates of the ‘age’ of the turbulence (defined as the ratio of transport time over the non-linear evolution time), which show that by 1 AU Alfvénic turbulence should have relaxed to ‘standard’ turbulence in fast winds, which is clearly not the case.

Another viewpoint, not necessarily contradicting the preceding one, consists in going beyond Alfvénic motions to identify different kinds of structures in the wind, such as fluctuations which maintain an overall pressure-balance, or slow and fast magnetosonic waves: the relative variations of the abundance of these different components in the wind have been related to the stream structure, heliocentric distance and solar activity.

3. Alfvén wave dynamics in the corona and solar wind

Alfvén waves as observed *in situ* in the solar wind always appear to be propagating away from the sun and it is therefore natural to assume a solar origin for these fluctuations. However, the precise origin in the solar atmosphere of the hypothetical source spectrum for Alfvénic turbulence is unknown, given the impossibility of remote magnetic field observations above the chromosphere-corona transition region. Although the spectrum of photospheric fluctuations is well documented, propagation of fluctuations upward is hindered by the highly structured nature of the medium, the very small scale height throughout the photosphere chromosphere and up to the solar corona, and the contemporarary fanning out of photospheric magnetic flux concentrations. Estimates based on simple properties of the MHD wave modes (Alfvén, fast and slow magnetoacoustic waves) indicate that they should have much difficulty even in reaching the solar corona: slow mode waves with periods greater than 5 minutes are evanescent, while waves with shorter periods steepen into shocks within the chromosphere. Fast magnetoacoustic modes which are non-parallel when propagating are totally reflected in the chromosphere and corona due to the rapid increase of the Alfvén speed with height in these regions (see, e.g., Narain and Ulmschneider 1996, Malara and Velli 1994 and references therein). Because of their highly anisotropic dispersion relation Alfvén waves do not suffer in the WKB limit from either of the above effects. In the presence of stratification, however, the wave propagation (Fourier transformed with respect to time) obeys a Schrödinger equation in which the role of the potential is played by the Alfvén speed gradient, and the transmission coefficient obtained assuming linear propagation through model atmospheres presents a broad minimum at periods between an hour and a few minutes, whose minimum value depends in detail on the assumed magnetic field expansion in moving from the chromosphere to the corona (Orlando *et al* 1996, Velli 1993). Spectra observed *in situ* do not seem to show any signature of atmospheric transmission, and this may be a clue that the Alfvénic spectrum is generated directly at the base of the solar corona perhaps by the ubiquitous impulsive activity which is observed (the ‘nanoflares’ coronal heating scenario) and subsequently evolves via non-linear interaction and compressible decay. Among the processes which could be of relevance here are the parametric decay instability, which we have recently shown to be a much more robust process than previously envisaged, both regarding the coherence of the mother wave spectrum (Malara and Velli 1996) and the propagation in an open section of the atmosphere with gravity (Pruneti and Velli 1997). In this picture, Alfvén waves are subject to parametric decay as they propagate outward through the solar corona, feeding energy into sound waves which may steepen and dissipate over extended regions. At the same time, the Alfvén wave flux may also be subject to the filamentation instability which leads in more than two dimensions to wave collapse, though for this process to be relevant in coronal heating frequencies higher than those typically considered to lie within the Alfvénic domain must be considered (Champeaux *et al* 1997 and references therein).

3.1. Alfvénic turbulence and the solar wind expansion

Non-linear Alfvén waves are defined as exact solutions of the homogeneous MHD equations (with uniform dc magnetic field) which have the following properties: the velocity field fluctuations are incompressible and aligned with the magnetic field fluctuations, there being perfect energy equipartition; in addition, the total pressure, thermal plus magnetic, is constant. The standard notation employs Elsasser variables $\boldsymbol{z}^{\pm} = \boldsymbol{v} \pm \boldsymbol{b}/(4\pi\rho)^{1/2}$, where $\boldsymbol{v}$, $\boldsymbol{b}$ are the velocity and magnetic field fluctuations; then $\boldsymbol{z}^{+}$ and $\boldsymbol{z}^{-}$ represent Alfvén waves propagating in opposite directions along the average magnetic field. When the large-scale structure is inhomogeneous (due, e.g., to the radial dependence of the density, temperature, etc. . .) the $\boldsymbol{z}^{\pm}$ modes no longer individually represent exact propagating perturbations. Still, it is best to consider the Alfvén wave as a reference state, in view of the observed dominance of Alfvénic periods in the solar wind, at least in the inner and polar heliosphere.

In the limit of very high frequencies, the linear WKB analysis of the evolution of Alfvén waves in a radially expanding spherically symmetric plasma flow predicts a frequency independent decrease of energy with distance. At low frequencies, the spherical expansion of the plasma acts differently on velocity and magnetic components, destroying the coherence of the waves, and a significant amount of reflection occurs, causing the energy fall off to become strongly frequency dependent. We have seen that in the solar wind, there is a spectral domain over which the observed decay of energy matches the WKB predictions, while the higher frequencies decay more rapidly because of non-linear interactions. This behaviour of the energy spectrum was first modelled successfully by Tu *et al* (1984) who wrote an equation for the evolution of the energy of the outward Alfvén propagating waves using a simplified scalar model for the non-linear interactions. The model equation shares with incompressible MHD the property of vanishing non-linear interactions when the inward mode is absent. To obtain non-linear evolution, Tu *et al* fixed the energy in inward propagating waves to a given fraction of the outward population. However, it is known that the ratio of inward to outward energies evolves, since the dominance of the outward component decreases with heliocentric distance. Within the framework of the solar wind expansion this experimental fact seems paradoxical, because both the non-linear terms of the original MHD equations (Dobrowolny *et al* 1980) and the linear WKB terms at the appropriate frequencies (Heinemann and Olbert 1980, Velli 1993) lead to an increase of the dominance of the outward component, at least for reasonable initial conditions.

A possible solution, suggested by Zhou and Matthaeus (1989), is that non-linear interactions, by destroying the coherence of the waves and therefore decreasing the linear (wave) coupling of velocity to magnetic fluctuations, might cause the expansion effects to increase in importance, effectively leading to an evolution resembling that of the low-frequency linear regime (see also Oughton and Matthaeus 1995, and the final paragraphs of Velli, 1993). Although this is an intriguing idea, the semi-empirical models developed so far appear to have severe difficulties in correctly describing the observations. In addition, such an analytical approach faces ever increasing complication when attempts are made to incorporate further important effects, also related to the expansion, such as the magnetic field rotation, and variation of the wavenumbers with distance, as studied by Volk and Alpers

(1973). A final comment concerns the behaviour of the lowest frequency fluctuations, which in the *Ulysses* magnetic field data (Smith *et al* 1995) appear not to decay (in energy per unit mass) with distance. This ‘quasi-static’ domain first predicted in the polar context in the framework of the scattering of cosmic rays by Jokipii and Kota (1989) is consistent with linear Alfvén evolution at such frequencies, and might prove an important probe into the wave source regions at the sun.

Another possible approach is the direct simulation of the MHD equations appropriate to solar wind conditions. Numerical simulations of the self-consistent wind problem including a fully resolved inertial range spectrum of fluctuations, in an Eulerian frame, clearly surpass the capabilities of existing computational facilities. The usual way to circumvent this problem is to follow the temporal evolution of the turbulence in a Lagrangian frame. In the solar wind, one also has the global expansion of the plasma. This may be taken into account (Grappin *et al* 1993, Grappin and Velli 1996) by considering a simplified model for the wind in which the average speed has reached its constant asymptotic value, which is roughly correct in the range $R > 0.1$ AU; if we follow a plasma parcel as it is advected, we will see its radial size remain constant and its transverse dimensions increase linearly with time. Additional simplifications are the adoption of a Cartesian frame of reference (the curvature of the plasma parcel is neglected) and periodic boundary conditions both in the transverse and radial directions: although this is valid only when the angular dimension of the parcel as seen from the sun is not too large, it will also be useful to describe the large-scale stream structure interactions. The resulting system of equations, which we name the expanding box model (EBM), correctly describes the linear wave evolution and average plasma cooling. The rotation of the wavevectors towards the radial direction and the rotation of the average magnetic field (cf Parker spiral) also arise naturally in this expanding box model. A number of interesting results may be obtained from purely one-dimensional (1D) simulations (the non-linear interactions occurring along an fixed axis in the coordinates comobile with the transverse expansion of a plasma parcel): although, in 1D, non-linear interactions are purely compressible and therefore should probably overestimate the level of density fluctuations generated, as well as yielding non-standard energy spectra. Suppose, then, one begins with maximal correlation of velocity and magnetic field and initial conditions corresponding to Alfvén waves propagating along the magnetic field at 0.3 AU, with varying initial rms Mach numbers of 0.3 and 0.6, as well as Alfvén waves propagating at an angle to the magnetic field. In the first two cases, the expansion is responsible for the onset of non-linear interactions, because the wavenumber and mean magnetic field turn within the ecliptic plane in opposite directions leading to a destruction of circular polarization. In the last case, the wave evolves non-linearly from the start because the total magnetic pressure is not constant. The results of the evolution are as follows (Grappin *et al* 1993): the energy in the outward propagating component follows the R^{-1} WKB law at first, but departs from it as soon as the z^- component becomes significant, which as expected, occurs earlier for the non-parallel propagating wave. The energy in the minor component E^- reaches levels largely above the linear prediction for wave reflection, which here would yield $E^-/E^+ = (\epsilon/8)^2 = 10^{-3}$ (ϵ, the ration of the average solar wind velocity divergence to wind speed, is a measure of the solar wind expansion rate). The evolution of the wave profile results in a complicated pattern involving discontinuities (one of which is pressure balanced) seen as jumps in the normalized velocity–magnetic field correlation $\sigma_c = (E^+ - E^-)/(E^+ + E^-)$ ($\sigma_c = 1$ initially). The expansion causes non-linear steepening for the highest Mach number $M = 0.75$, but delays and decreases the excitation of small scales for non-parallel propagating waves. The non-linear transfer corresponds to a ‘turbulent’ heating which makes the temperature decay slower than the $R^{-4/3}$ adiabatic law. The turbulent heating is completely negligible for the Alfvén wave with $M = 0.3$, but quite a significant departure is seen for $M = 0.75$, both for the Alfvén and mixed cases. The non-linear evolution of Alfvén and fast and slow magnetoacoustic waves for more general propagation angles has also been investigated using the EBM (Schmidt *et al* 1996). The three types of eigenmodes show very different decay laws: slow modes decay slowly with heliocentric radial distance, fast modes rapidly, and Alfvén modes in between (as $1/R$ or slightly faster). As a rule, the cross-helicity is not a good indicator of non-linear evolution; except at initially very large angles between wavevector and mean field, the wave cross-helicity does not depart much from its initial value, in spite of the formation of small-scale excitation, tangential discontinuities or shocks. But quasi-parallel propagating low-amplitude slow and fast magnetoacoustic waves show a quite pure large-scale oscillation in Alfvénicity due to non-linear interactions alone, leading to relative directional turnings between the velocity polarization of the fluctuations and the mean magnetic field.

4. Turbulence driven by structures

We have seen above that one of the difficult processes to understand is the decrease in the ratio of the energies in the outwardly and inwardly propagating waves with increasing distance from the sun. The original idea was that the turbulent spectral range (including in particular the Alfvén range) arises through a turbulent cascade resulting from the Kelvin–Helmholtz instability in stream shears. Roberts *et al* (1987), in their analysis of the solar wind data, proposed that the instability of the large-scale (stream shear) velocity gradients was indeed responsible for such an energy cascade, which would create new small-scale excitation, with little or no outward dominance, thus reducing the overall correlation coefficient. Roberts *et al* (1991) carried out two-dimensional simulations of a radial cut of the heliosphere containing a slow flow imbedded within two fast streams. The simulation included a weakly varying magnetic field, with no current sheet. Later, Roberts *et al* (1992) considered a case with a magnetic neutral sheet, showing that the decay of correlation is accelerated near the neutral sheet. This was interpreted as proof that a non-linear quasi-incompressible cascade is able to produce the *in situ* observed variation of turbulence with distance from the heliospheric current sheet. A different viewpoint for interpreting the decay of a set of purely outward propagating waves was adopted by Malara *et al* (1992). They proposed that the main process which makes the outward population evolve is not a standard turbulent cascade, but the direct interaction between the small-scale waves and the large-scale gradients. They start with a stable magnetic configuration, no stream shear, and follow the evolution of the wave spectrum propagating in the large-scale magnetic gradient. As in the preceding case, the cross-helicity is progressively reduced at places where a compressive component appears. This interpretation probably also holds true for the simulations of Roberts *et al* (1992), which display a remarkably constant energy at the largest scales and the formation of an inward propagating spectrum at all scales at once, in about one Alfvén time. Similar evolution is also displayed when the stream shear is allowed to evolve in the expanding box, where in addition one observes the strong emergence of magnetically dominated fluctuations in regions of weak magnetic field (Grappin and Velli 1996). In more recent simulations which also contain the solar wind stream structure and a more realistic model for the current sheet, but still without inclusion of solar wind expansion effects, Malara *et al* (1996) show how Alfvén-type correlations are progressively destroyed in the current sheet and how the stream region becomes progressively populated with slow-mode type fluctuations confined by the gradients in average fields, leading to pressure-balanced structure which appear to be well correlated with the sites where they are observed.

5. Conclusions

We have presented a description of the evolution of MHD fluctuations and turbulence in the solar corona and wind, and compared in and out of ecliptic observations with results obtained from theoretical models and numerical simulations. The *Ulysses* spacecraft has confirmed the dominance of outward propagating Alfvén waves in the turbulence in the polar regions of the heliosphere. The origin of such waves must be attributed to the sun, and they may well be the remnant of a flux which plays a fundamental role in the acceleration of the high-speed wind which dominates at high heliospheric latitudes. A detailed description of the turbulence is being carried out at present (see, e.g., the special issue of *Geophys. Res. Lett.* (1995) as well as the proceedings of the Solar Wind 8 conference (1996)) but the theoretical instruments necessary for the interpretation of such measurements are reaching a competitive stage (EBM). What is lacking is a fully Eulerian wind tunnel which should fully describe the solar wind acceleration as well as the evolution of the turbulence. Work in that direction is currently being carried out.

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