Ann. Geophys., 24, 785–789, 2006
www.ann-geophys.net/24/785/2006/

Annales Geophysicae

Alfvénic turbulence in solar wind originating near coronal hole boundaries: heavy-ion effects?

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Received: 10 October 2005 – Revised: 30 January 2006 – Accepted: 2 February 2006 – Published: 23 March 2006

Abstract. The mid-latitude phases of the Ulysses mission offer an excellent opportunity to investigate the solar wind originating near the coronal hole boundaries. Here we report on Alfvénic turbulence features, revealing a relevant presence of in-situ generated fluctuations, observed during the wind rarefaction phase that charaterizes the transition from fast to slow wind. Heavy-ion composition and magnetic field measurements indicate a strict time correspondence of the locally generated fluctuations with 1) the crossing of the interface between fast and slow wind and 2) the presence of strongly underwound magnetic field lines (with respect to the Parker spiral). Recent studies suggest that such underwound magnetic configurations correspond to fast wind magnetic lines that, due to footpoint motions at the Sun, have their inner leg transferred to slow wind and are stretched out by the velocity gradient. If this is a valid scenario, the existence of a magnetic connection across the fast-slow wind interface is a condition that, given the different state of the two kinds of wind, may favour the development of processes acting as local sources of turbulence. We suggest that heavy-ion effects could be responsible of the observed turbulence features.

Keywords. Interplanetary physics (MHD waves and turbulence; Solar wind plasma) – Space plasma physics (Turbulence)

1 Introduction

Ulysses observations over two out-of-ecliptic orbits at different phases of the Sun's activity cycle have clearly established that the solar wind, though dramatically different between minimum and maximum conditions, for a major fraction of the cycle around solar minimum exhibits an almost unchanged pattern (McComas et al., 2002a,b). This corresponds to a bimodal regime, with a fast and uniform flow filling large angular sectors at high heliographic latitudes (the so-called polar wind) and slower, more variable, flows in a belt around the equatorial plane (McComas et al., 2000). The boundary between these two kinds of wind is located at latitudes between 15° to 30°.

An ideal opportunity for a detailed study of the transition between the fast high-latitude wind and the slow low-latitude wind is offered by the mid-latitude phases of Ulysses around the aphelion, when the spacecraft, moving slowly in latitude, spends several solar rotations in the region of interest. This leads to repeated crossings of the interface between the two flows, seen as a series of compression (slow to fast transition) and rarefaction (fast to slow transition) regions. Obviously, in the presence of coronal hole extensions towards the solar equator this kind of study can be also done with observations by spacecraft located near the ecliptic plane (e.g. Burlaga et al., 1978, Schwenn et al., 1978), but the use of Ulysses measurements allows to directly focus on the the latitudinal belt in which the transition region as a whole is located (with exception of periods near the solar activity maximum).

The interface between the two kinds of wind surely is an interesting place to study turbulent processes in the solar wind. This region may be seen as a counterpart of the polar wind region. The latter, filled with a quite uniform flow, is very suitable to study how turbulence evolves in a nearly unperturbed plasma. In contrast, at the boundary between different flows strong inhomogeneities in the plasma parameters may lead to the development of local turbulence effects. Here we limit our study to briefly report on some specific features of the Alfvénic turbulence observed near the stream interface within rarefaction regions. The effect of scale expansion in these regions is a favourable condition to investigate in detail the nature of the transition. In future studies, by comparing rarefaction regions at or inside 1 AU to Ulysses observations further out, we plan to investigate the evolution of turbulence in the evolving sub-Parker spiral structures.

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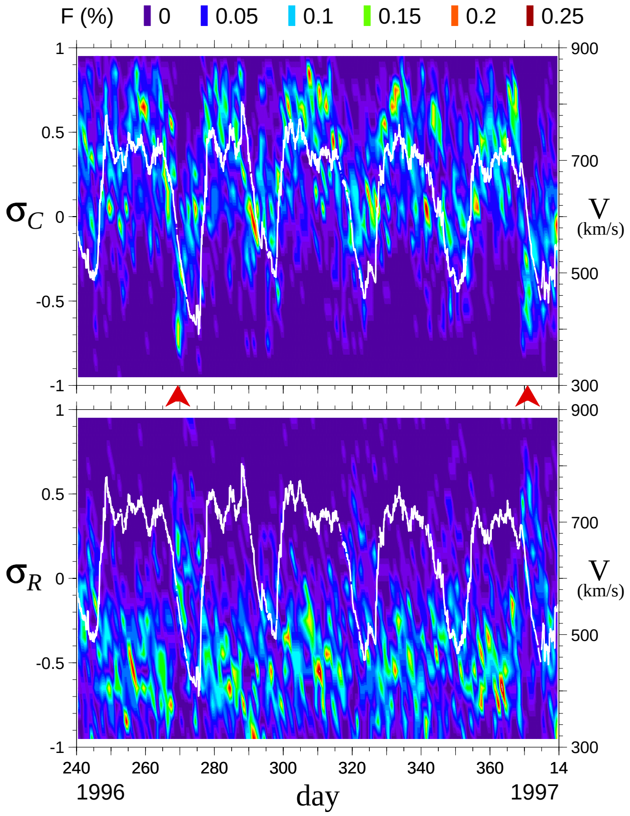

Fig. 1. Daily occurrence frequency F of σ_C (top panel) and σ_R (bottom panel) hourly values for days 240 (1996) to 14 (1997), during the Ulysses's second distant mid-latitude phase. In both panels a white line shows the solar wind velocity magnitude V.

It is worth recalling that the solar wind Alfvénic turbulence is a mixture of two different populations, one made of fluctuations propagating, in the wind plasma frame, away from Sun (outward population) and the other of fluctuations going towards the Sun (inward population). In general the outward population is strongly dominant in terms of energy per unit mass (e.g., see reviews by Tu and Marsch, 1995, and Bruno and Carbone, 2005). Outside the Alfvénic critical point (where the solar wind becomes super-Alfvénic) both kinds of fluctuation are obviously convected outwards as seen from the Sun. The major source for outward fluctuations is the Sun, however contributions also come from interplanetary processes. Conversely, inward fluctuations can only originate from sources in the region outside the Alfvénic critical point, since inside this point inward waves fall back to the Sun.

2 Observations

The parameters generally used to study Alfvénic fluctuations are the energies per unit mass of the outward (e_+) and inward (e_-) Alfvénic population, together with those of the velocity (e_V) and magnetic field (e_B) fluctuations (these last ones scaled to Alfvén units by the dividing factor $\sqrt{4\pi\rho}$, with ρ the mass density). They are computed as total variance (trace of the variance matrix) of the corresponding fluctuation vectors on a given averaging time (for details on the analysis method see Bavassano et al., 2005). From these energy values the normalized cross-helicity $\sigma_C=(e_+-e_-)/(e_++e_-)$ and the normalized residual energy $\sigma_R=(e_V-e_B)/(e_V+e_B)$ are promptly derived. Results discussed here refer to hourly-scale fluctuations, in other words hourly variances are used to evaluate e_+, e_-, e_V, and e_B. With this choice we are focusing on fluctuations in the core of the solar wind Alfvénic regime (Tu and Marsch, 1995).

In Fig. 1 we give an overview of the σ_C and σ_R values for a 140-day interval during the second distant (or, near aphelion) mid-latitude phase of Ulysses, when the spacecraft, after the northern polar crossing, was travelling back to the equator. At that time, with the solar activity at a minimum, the corona appears to be exceptionally stable, offering very favourable conditions to study the solar wind originating from solar regions close to coronal hole boundaries. The Ulysses' heliographic latitude and heliocentric distance vary, for the plotted interval, from 28.0° to 18.2° (North) and from 4.26 to 4.75 astronomical units, respectively. Daily histograms of hourly σ_C and σ_R values are shown versus time in the upper and lower panel, respectively. In both panels a white line gives the solar wind velocity.

The well known dependence of σ_C on the solar wind velocity regime, with large positive values within fast streams and close to 0 values in slow streams, and the well established predominance of negative σ_R values (e.g. Tu and Marsch, 1995) are easily recognized and will not be further discussed. The points that we would like to stress here are 1) the appearance of time intervals in which a negative σ_C (i.e., $e_->e_+$) is a dominant feature, and 2) the fact that this tends to occur inside rarefaction regions. The effect is particularly pronounced close to days 269, 1996, and 5, 1997 (see red arrowheads at the bottom of σ_C panel). The unusual negative σ_C events are also characterized by equally unusual values of σ_R ($\sim$0 or even positive).

As already discussed in the introduction, the negative σ_C excess can only be the result of interplanetary processes. It is well known that inward fluctuations originate in a variety of solar wind flows, including rarefaction regions (e.g. Roberts et al., 1987). Velocity shear has been often indicated as a natural candidate for generating interplanetary fluctuations (Roberts et al., 1992), however also other mechanisms may be at work (Tu and Marsch, 1995). For the two cases indicated by red arrowheads in Fig. 1 we have decided of investigating if the stream interface may be a relevant element of the processe(s) responsible for the observed turbulence behaviour. To this aim in Figs. 2 and 3 we show time plots of solar wind and turbulence parameters for 15-day intervals around the two events highlighted in Fig. 1. From top to bottom the panels give 1) the solar wind velocity magnitude

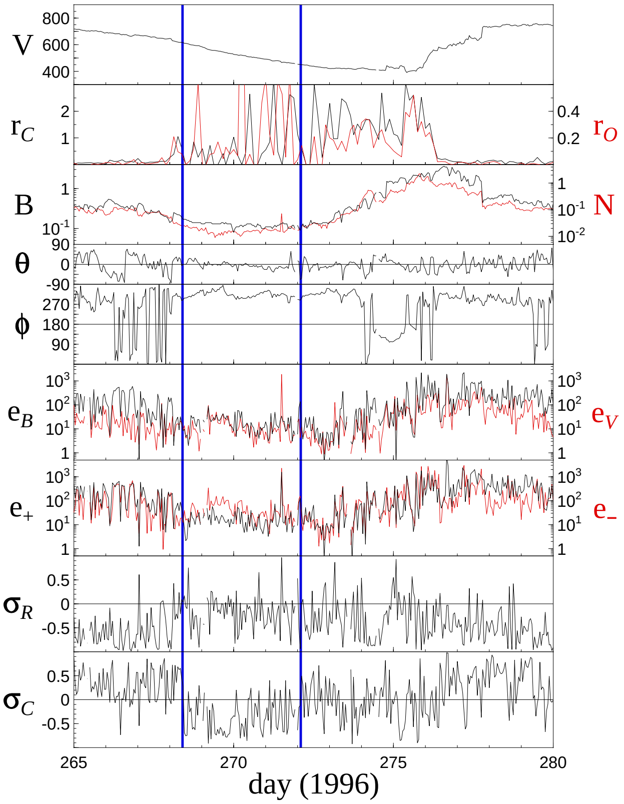

Fig. 2. Solar wind data and turbulence parameters vs. time as observed by Ulysses for days 265 to 280 (1996). For a detailed description see the text.

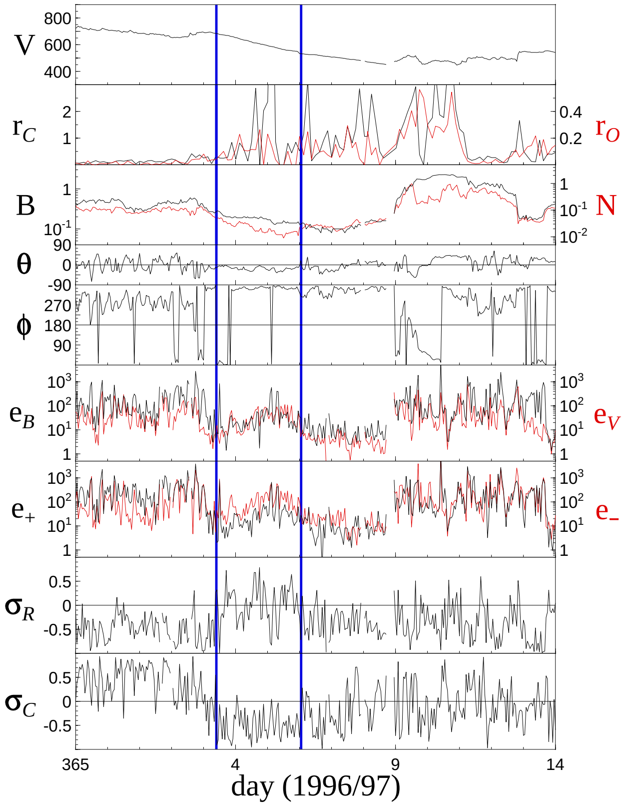

Fig. 3. Solar wind data and turbulence parameters vs. time as observed by Ulysses for days 365 (1996) to 14 (1997), in the same format as Fig. 2.

V (in km/s), 2) the ion abundance ratios r_C (C^{6+}/C^{5+}) and r_O (O^{7+}/O^{6+}, red curve), 3) the magnetic field magnitude B (in nT) and the proton number density N (in cm^{-3}, red curve), 4) the magnetic field latitude θ (in degrees), 5) the magnetic field longitude ϕ (in degrees), 6) the e_B and e_V (red curve) fluctuation energies (in km^2/s^2), 7) the e_+ and e_- (red curve) fluctuation energies (in km^2/s^2), 8) the normalized residual energy σ_R, and 9) the normalized cross-helicity σ_C. Note that the magnetic field latitude and longitude are given in the heliospheric RTN coordinate system (R-axis along the Sun-Ulysses line and positive away from the Sun, T-axis given by the cross-product of the solar rotation axis with the R-axis, and N-axis defined to complete the rigth-handed system). All the plotted quantities have an one-hour time resolution, with the exception of the ion abundance ratios r_C and r_O (three-hour values).

For the rarefaction region shown in Fig. 2 the presence of negative σ_C and close to zero σ_R values is a common feature for a period of almost four days (highlighted by blue lines). The best examples of this state of turbulence are seen on day 269, when for about twelve hours σ_C ranges from –0.7 to –0.6 and σ_R from –0.3 to 0.2. From the e_+–e_- panel (third from bottom) it is easily recognized that this σ_C behaviour comes from an increase of e_- (red curve), with e_+ remaining nearly unchanged. All this occurs in concurrence with 1) the start of rising levels in the ion abundance ratios r_C and r_O, and 2) close-to-radial magnetic field intervals.

As pointed out by Geiss et al. (1995) and von Steiger et al. (2000), the level of the ion charge-state ratios is a good parameter to distinguish fast wind associated to coronal holes from slow wind associated to the streamer belt, with low (high) values of C^{6+}/C^{5+} and O^{7+}/O^{6+} indicative of fast (slow) wind. Thus, point 1 indicates that just near the beginning of the blue-line interval the spacecraft is crossing the stream interface. As regards point 2, numerous examples of a magnetic field more radial than the Parker's spiral (sub-Parker spiral) have been reported in the literature (e.g., see references in Gosling and Skoug, 2002). Not surprisingly, these events tend to occur within rarefaction regions. In general, as is obvious, the magnetic field azimuthal angle can be greater or smaller than the Parker's spiral angle depending on the magnetic field direction and speed gradient near the Sun (Burlaga and Barouch, 1976). However, for the case shown in Fig. 2 (and also for the other events examined below) the trend towards a magnetic field more radial than the Parker's spiral occurs in a strict connection with the crossing of the

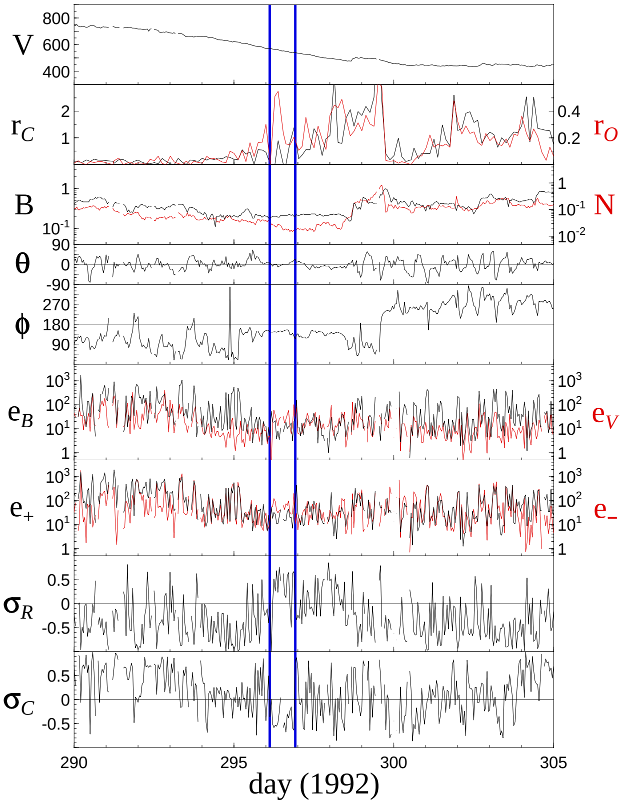

Fig. 4. Solar wind data and turbulence parameters vs. time as observed by Ulysses for days 290 to 305 (1992), in the same format as Fig. 2.

stream interface. This is reminiscent of a scenario recently proposed by Schwadron (2002) and Schwadron and McComas (2005) to give account of sub-Parker magnetic lines. In their view the strongly underwound magnetic fields could be explained in terms of a foot-point motion of open magnetic lines at the Sun across the coronal hole boundary. Such motions cause magnetic field lines to be connected and stretched across the fast-slow wind interface, creating a less underwound magnetic spiral (note that interchange reconnection may also play a role in this kind of phenomena, see Gosling and Skoug, 2002). As stressed by Schwadron et al. (2005), the presence of a magnetic connection across the stream interface can have relevant effects on the behaviour of the surrounding plasma since the two regions are remarkably different for several respects, in particular their elemental and charge state composition (Geiss et al., 1995). A magnetic connection between such regions is a condition favouring the growth of processes driven by the existing gradients. If this is a valid scenario, it does not seem unreasonable to think that these processes, besides to a gradient erosion, can also lead to turbulence effects as those mentioned above.

These comments essentially hold also for the interval between blue lines in the rarefaction region shown in Fig. 3, that corresponds to the red arrowhead on the right in Fig. 1. This is the same event analysed by Jones et al. (1998) in one of the first studies on close-to-radial magnetic fields. An interesting feature of this case is that e_+ and e_- exhibit quite similar trends, with a broad peak just in coincidence to a large value (about nine) of the C^{6+}/C^{5+} ratio.

Finally, though in the present analysis we focus on the second distant mid-latitude phase of Ulysses in 1996-1997, we would like to stress that cases similar to those shown in Figs. 2 and 3 are observed also during the first distant mid-latitude observations in 1992–1993. An example is shown in Fig. 4, referring to days 290 to 305, 1992. Negative σ_C and positive σ_R values are seen just near the stream interface (see blue lines), during an interval of sub-Parker magnetic spiral. The period plotted in Fig. 4 belongs to the stream used by Schwadron et al. (2005) to test their model on the effect of magnetic footpoint motions. Figure 3 in their paper clearly shows that a differential streaming of heavy ions is predicted to develop around day 296, namely in connection with the blue-line interval of Fig. 4.

3 Concluding remarks

The Alfvénic turbulence seen in solar wind flows originating from solar regions near the polar coronal hole boundaries is often characterized by a negative cross-helicity and a nearly zero (or sometimes positive) residual energy. We have given examples showing that this unusual behaviour is seen to occur just near the crossing of the stream interface and in concurrence with periods of sub-Parker magnetic field spiral (magnetic field lines more radial than for the Parker's spiral).

Recent studies (e.g. Schwadron, 2002; Schwadron and McComas, 2005) have suggested that footpoint motions at the Sun across the coronal hole boundary are the underlying cause of the sub-Parker spiral. Field lines originally in the fast coronal-hole flow have their inner leg transferred to slow wind. This leads to magnetic field lines that connect fast to slow wind across the stream interface and are stretched out by the velocity gradient more than the Parker spiral, with the result of a more radial magnetic field.

Assuming that this is a valid scenario, the presence of a magnetic connection across the stream interface is a condition favouring the growth of plasma processes that tend to wash out the strong gradients existing between fast and slow solar wind. We suggest that these processes might act as local sources of turbulence and account for the observations discussed above. In this regard it is important to stress how, for the event shown in Fig. 4, the interval with unusual values of σ_C and σ_R just corresponds to the region where, following the model of Schwadron et al. (2005), a differential streaming of heavy ions develops. However, at present a model on how the ion streaming might be responsible of the observed Alfvénic features is not available.

Rarefaction regions are known to exhibit continuous transitions across their stream interface, a condition required by the second law of thermodynamics. The microphysics underlying this continuous transition is not well known, particularly in the solar wind. Here, we are revealing the underlying physical character of turbulence along sub-Parker spiral magnetic field lines. The unusually strong inward component that they exhibit might be critical to setting up the necessary continuous transition between fast and slow solar wind.

Acknowledgements. The use of data of the plasma analyzer (principal investigator D. J. McComas, Southwest Research Institute, San Antonio, Texas, USA), of the ion spectrometer (principal investigators G. Gloeckler, University of Maryland, College Park, Maryland, USA, and J. Geiss, International Space Science Institute, Bern, Switzerland), and of the magnetometers (principal investigator A. Balogh, The Blackett Laboratory, Imperial College, London, UK) aboard the Ulysses spacecraft is gratefully acknowledged. The data have been made available through the World Data Center A for Rockets and Satellites (NASA/GSFC, Greenbelt, Maryland, USA). The present work has been supported by the Italian Space Agency (ASI) under contract I/035/05/0 ASI/INAF-OATO.

Topical Editor B. Forsyth thanks L. Svalgaard and E. Lucek for their help in evaluating this paper.

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