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Particle channels in the solar wind: Magnetic field fluctuations, wave refraction and dissipation

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Abstract. Buttighofer has reported the existence of "channels" in the solar wind through which solar energetic particles can propagate almost scatter-free. We draw attention to an event observed by the ACE spacecraft on May 11 1999 that has many of the characteristics of Buttighofer's channels. The ACE event is known as 'The Day the Solar Wind (Almost) Disappeared'. During this unusual rarefaction event, the solar wind density dropped by almost 2 orders of magnitude relative to the value that is typically seen at ACE. However, the magnetic field remained almost constant during the rarefaction. The most striking feature of the magnetic field as measured by ACE was the fact that the r.m.s. (root mean square) field fluctuations dropped to unusually low values (about 0.1 nT). These low r.m.s. values are reminiscent of the behavior reported by Buttighofer in the particle channels. Moreover, the fluctuations that remained in the ACE rarefaction region were found to be significantly more transverse to the mean field than usual, again analogous to a feature reported by Buttighofer in the channels. We suggest that the phenomenon of refraction allows us to understand the properties of the magnetic fluctuations inside the ACE rarefaction region, and by extension, in the Buttighofer particle channels as well.

1 Introduction

The propagation of energetic particles through the solar wind is controlled by the properties of the fluctuating magnetic fields through which the particles move. So much so that certain significant properties of the fluctuations can be derived from the properties of cosmic ray transport (e.g. Bieber et al. 1996). When the magnetic field is highly disturbed, and the fluctuations are large, particles from the Sun undergo severe scattering in the wind.

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1.1 Scatter-free channels

However, there are also periods when the particles appear to propagate through the wind in an almost scatter-free fashion. A sample of such periods has been highlighted by Buttighofer (1998). Using Ulysses electron data, Buttighofer reported that energetic electrons from solar flares retained large anisotropies even when Ulysses was at distances of 4-5 AU (astronomical units) from the Sun. To reach Ulysses at such distances, the electrons must have propagated along spiral paths with lengths of some 10 AU without losing their initial collimation. This indicates that pitch angle diffusion must have been unusually weak along pathlengths of many AU in each event. Buttighofer refers to the solar wind regions in these events as "propagation channels".

The main characteristic of the propagation channels to which Buttighofer (1998) drew attention was their very low level of magnetic fluctuations. Quantitative spectral analysis of the magnetic fields in the propagation channels (Buttighofer et al. 1999) indicated that indeed the spectral power density of the magnetic fluctuations inside the channels is about 10 times lower than the spectral power density outside. Moreover, the spectral analysis also revealed that the loss of spectral power inside the channels is due to a reduction in one particular of fluctuations, namely, the compressible components. In contrast, the incompressible fluctuations remained at comparable levels inside and outside the channels. Buttighofer et al. 1999 pointed out that since compressional fluctuations are efficient at pitch angle scattering, the reduced levels of such fluctuations inside the channels would allow particles to propagate more easily in a scatter-free regime.

The spectral analysis indicated that the slopes of the magnetic power spectra were not significantly different inside and outside the channels. As a result, Buttighofer et al. concluded that the scatter-free nature of particle propagation inside the channels results not from a change in spectral slope (compared to the conditions outside), but from the 10-fold reduction in overall power level. However, Buttighofer et al. 1999 pointed out that differences in the spectral shapes inside and outside the channels might occur at higher frequencies than they could study with Ulysses data.

Another feature of the channels is that the particle densities in the channels are somewhat lower than in typical solar wind.

Buttighofer et al (1999) made some suggestions as to how the particle channels might arise in the solar wind. However, no definitive conclusions as to their origin were drawn. Here, we suggest that by studying a particular interval of solar wind near 1 AU, we may be able to increase our understanding of this matter.

2 The day the solar wind (almost) disappeared

On May 10-12 1999, the ACE spacecraft was engulfed by a remarkable parcel of solar wind plasma. Over the course of 24-36 hours, the density in this parcel fell steadily, until, late in the day on May 11 1999, the density had values of only 0.1 /cc, almost 2 orders of magnitude more rarefied than normal. The density remained at the 0.1/cc level for an interval of some 6 hours. Then in the course of 12-18 hours on May 12, the density recovered to its typical value.

Inside this rarefaction region (R.R.), the magnetic field magnitude was not remarkable: it had typical values (5-7 nT). The most striking aspect of the magnetic field during the R.R. was the low level of fluctuations in the field: analysis of the ACE magnetometer data indicates that B(r.m.s.) also declined as the density was declining, reaching minimum values of order 0.1 nT during the period of lowest density. A survey of the ACE magnetometer data set for a two-year interval indicates that no more than 1-2 percent of ACE data contains B(r.m.s.) as low as 0.1 nT. The R.R. was truly a region of exceptionally quiet magnetic fields. In this regard, the R.R. reproduces the first property of Buttighofer's channels.

A second property of Buttighofer's channels which appears in the R.R. is the reduction in density compared to neighboring wind. To be sure, the reductions of density reported in Buttighofer's channels are by no means as extreme as the 100-fold reduction in the R.R. But the channels are sites of reductions in density nevertheless.

A third property of the Buttighofer channels emerges in the R.R. when we examine the anisotropy of the magnetic fluctuations. Taking the r.m.s. values of the fluctuations perpendicular and parallel to the mean field direction, we find that the ratio of perpendicular to parallel amplitudes is 20-30 in the R.R. Compared to the typical value of this ratio in the solar win (5-10), it is apparent that the magnetic fluctuations in the R.R. are significantly more transverse (incompressive) than in the typical wind. Moreover, just outside the R.R., the ratio falls to 2-3, i.e. significantly more parallel (compressive) than in typical wind.

To highlight further the incompressive nature of the fluctuations inside the R.R., we obtained power spectral densities from the ACE magnetometer data. Not only are the overall levels of fluctuation power reduced inside the R.R., but the parallel power spectra are reduced by a further factor of 10 inside the R.R. compared to outside.

2.1 Shifts in the dissipation range

Finally, the ACE spectra allow us to examine the dissipation range of the spectra: inside the R.R. we see that the break in the spectra that is believed to be associated with the onset of dissipation shifts to lower frequencies (in the spacecraft frame). This down-shift is not a marginal effect: statistically, the shift is at the 10 sigma level or better.

3 Refraction of fast-mode MHD waves

The properties of the solar wind inside the R.R. are consistent with refraction of fast-mode MHD waves (Smith et al. 2001). The combination of low density and normal magnetic field strengths has the effect that the Alfven speed is exceptionally large inside the R.R. Also in the Buttighofer channels, the Alfven speed inside the channels is clearly larger than the value outside.

3.1 Uchida's theory

In order to appreciate the significance of localized enhancements in Alfven speed, we refer to work by Uchida (1968). In an attempt to interpret the propagation of certain types of flare-induced ("Moreton") waves in the solar atmosphere, Uchida developed a theory for the propagation of fast-mode MHD waves in a medium containing spatial gradients of Alfven speed. Uchida showed that the relevant equations are analogous to those describing the dynamics of a particle in a region of varying potential wells. As far as wave propagation is concerned, a local enhancement in Alfven speed has the same effect as a hill on the motion of a particle. The particle is repelled by such a hill, and by analogy, fast-mode waves are refracted away from regions of large Alfven speed. Uchida showed that this provides a useful tool in interpreting the observed properties of Moreton waves. More recently, it has also been found useful in understanding the coronal propagation of EIT waves (Thompson et al. 1999).

Here, we apply Uchida's theory to conditions in the solar wind. Because of refraction, fast-mode waves are excluded from the R.R. and from the Buttighofer channels. We suggest that this exclusion of an entire class of MHD fluctuations may explain why the level of magnetic fluctuations is so low inside both regions.

In contrast to fast-mode waves, Alfven waves are not subject to the same refraction process. There is therefore no reason for them to be excluded from the R.R. by the Uchida mechanism.

In our ACE magnetometer data, we find evidence that fast-mode waves pile up just outside the R.R., while Alfven waves are relatively more abundant inside the R.R (see Smith et al. 2001). Buttighofer's discovery of reduced levels of all fluctuations inside the particle channels, combined with even more reduced levels of compressive fluctuations, is consistent with the refractive exclusion of fast-mode waves, but lack of exclusion of Alfven waves.

4 Cosmic ray transport in high-Alfven speed channels

Because of refraction, the overall level of magnetic fluctuations (especially compressive modes) inside the channels is reduced. This contributes to reduced pitch-angle scattering of cosmic rays.

If the particle channels are analogous to the R.R. also in the sense that there is a reduction in the frequency of the break-point at which dissipation sets in, then we may also point to another contributor to reduced scattering of particles. Smith et al. (1990) have shown that cosmic ray scattering depends on the properties of the dissipation range. Based on their work, it is expected that in a plasma parcel where the dissipation onset frequency is lower than in the surrounding medium, the efficiency of particle scattering will be reduced.

If our interpretation is correct, channels of scatter-free propagation in the solar wind should be identifiable most readily in terms of an unusually large Alfven speed.

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5 References

Bieber, J.W., et al., Dominant 2-D Solar Wind Turbulence with Implications for Cosmic Ray Transport, *J. Geophys. Res., 101,* 2511-2522, 1996.

Buttighofer, A., Solar Electron Beams Between 1 and 4 AU, *Astron. Ap. 335*, 295-302, 1998

Buttighofer, A., et al., Spectral analysis of fields inside propagation channels, *Astron. Ap. 351*, 385-392, 1999.

Smith, C. W., et al., Cosmic ray scattering. II. Dependence on the dissipation range spectra, *ApJ., 363*, 283-291, 1990.

Smith, C. W. et al., The day the solar wind (almost) disappeared, *J. Geophys. Res*. (in press), 2001.

Thompson, B.J., et al., SOHO/EIT Observations of the 1997 October 7 Coronal Transient, *ApJ., 517*, L151-154, 1999.

Uchida, Y. Propagation of Hydromagnetic Disturbances in the Solar Corona and Moreton's Wave, *Solar Phys., 4,* 30, 1968.