Spatial Intensity Gradients of Impulsive Particle Events and Supradiffusive Magnetic Fields

B. R. Ragot[1] and S. W. Kahler[2]
(1) Department of Astronomy, University of Texas, Austin, TX 78712, USA
(2) Space Vehicles Directorate, Air Force Research Laboratory, 29 Randolph Road, Hanscom AFB, MA 01731, USA

Abstract

The low-energy ion intensity profiles of impulsive solar energetic particle (SEP) events display both sharp (< 2.5 min) local gradients and larger scale ($\approx 1-6$ hour) dropouts, indicative of fast cross-field transport on the larger scales in spite of restricted short-scale transport. Rapid variations and modulations within the few-hour long channels of enhanced intensity are also observed. We show that these features are a signature of strong supradiffusion of magnetic field lines in the inner heliosphere.

1. Introduction

Observations of 20 keV nuc^{-1} to 5 MeV nuc^{-1} impulsive solar flare ions with the ACE spacecraft at 1 AU have allowed the study of magnetic connections to flares over much longer timescales than previously possible [2]. Temporal structures were found in the intensity profiles of the SEP ions, with large intensity peaks and dropouts on $1-6$ hour scales, characteristic of mixed magnetic flux tubes successively filled and devoid of flare ions, as well as much finer structures within the magnetic flux tubes and sharp (< 2.5 min) gradients at the interfaces between filled and empty channels. These structures exist because of the very small extent of the flare ion source region and are not observed in gradual SEP events [2], in which all spanned magnetic flux tubes are equally filled with energetic ions at the source.

A reasonable account of the large-scale peaks and dropouts has been given [1] in terms of magnetic flux-tube mixing and footpoint motion at the supergranulation scale L_S. However, the model of Giacalone et al. [1], in which the field lines are regular on scales shorter than $L_S(R/R_\odot)^2$ and the transport on these shorter scales is due entirely to particle cross-field scattering, explains neither the smaller-scale irregularities observed within the large hour-long channels nor the fact that those irregularities, as well as the sharp gradients at the channel boundaries, do not seem to vary with the energy of the particles. If indeed no small or medium-scale transport occurred other than the short-scale particle cross-field

pp. 3531–3534

scattering, then the observations should show large channels with steep gradients at their boundaries, but no irregularities other than statistical fluctuations within the channels. However, the variations and irregularities of the intensity profiles discussed by Mazur et al. [2] suggest the presence of many fine substructures of the magnetic field flux tubes.

Pure cross-field scattering of charged particles depends on the particle gyroradius, hence on energy, but no such dependence was observed by Mazur et al. [2]. While energy-dependent gradients could be much shorter than the available 2.5 -min time resolution, the observed gradients may be the true scale gradients, but due to the short-scale structure of the spreading field lines rather than to particle cross-field scattering, and therefore independent of the particle energies. In any case the sharp gradients should not be attributed to particle cross-field scattering alone without first assessing the contribution from the short-scale magnetic field-line wandering to the cross-field transport of particles. Between the range of small turbulent scales responsible for the cross-field scattering of the particles and the large-scale $L_S(R/R_\odot)^2$, there is a broad gap in the solar-wind turbulence spectrum to be accounted for. We now estimate the effects of this range of magnetic turbulence on field-line wandering.

2. Supradiffusive Field Lines and Magnetic Substructures

Quasilinear calculations for the spreading of turbulent magnetic field lines have been generalized by Ragot [3,5] to turbulence spectra of arbitrary shape. The effects of any part of the turbulence spectrum can now be quantified, and the use of propagators such as given in Ragot [4] allows one to study the distribution of magnetic field lines on any given scale. Denoting by $\langle \Delta r^2 \rangle$ the average spreading of the field lines across the direction of the mean field, the transport exponent is defined as $\beta = d(\log\langle \Delta r^2 \rangle)/d(\log \Delta z)$. Fig. 1a shows the transport exponent β resulting from a "typical" interplanetary spectrum of turbulence for a broad range of the length scale Δz taken along the average direction of the field on that particular length scale. We see that for $10^9\,\mathrm{cm} < \Delta z < 10^{13}\,\mathrm{cm}$ the transport exponent β displays strong variations with Δz, and significantly departs from the diffusive value of 1. Magnetic field lines in the solar wind are supradiffusive ($\beta >$ 1) as long as a quasilinear regime of turbulence remains a good approximation. This supradiffusion and associated average cross-field displacement (see Fig. 1b) produce an enhanced intertwining (on all scales from the boundaries) between the filled and empty magnetic flux tubes.

In Fig. 1b we use an estimate of the transport coefficient $D_\beta \approx \langle \Delta r^2 \rangle/(\Delta z)^\beta$ based on results of Fig. 1a to evaluate the size and sharpness of the magnetic field structures that can develop on the length scale Δz from an initially narrow bundle of field lines. The rescaled spatial distributions plotted in Fig. 1b are obtained from the propagators of transport exponent $\beta(\Delta z)$ and of transport coefficient

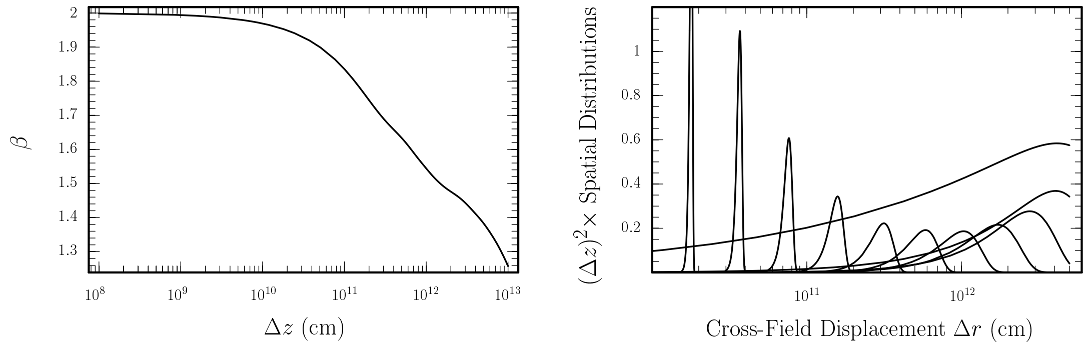

Fig. 1. (a) Transport exponent β as a function of the length scale Δz along the average magnetic field for a typical turbulence spectrum of the inner heliosphere. (b) Spatial distributions $\times(\Delta z)^2$ of initially narrow bundles of magnetic field lines across the average field at a series of scale lengths $\Delta z = 2^{-n}$ AU with $n = 0, 2, ...10$.

D_β for a series of length scales $\Delta z = 2^{-n}$ AU with $n = 0, 2, ...10$.

3. Discussion and Conclusion

Transport equations and their solutions are *valid only beyond* the typical length scale over which the regime of transport is established. For the familiar example of diffusive field lines that characteristic length scale is a few times the correlation length L_c. To that correlation length corresponds a transverse scale length X_c. The point here is that the smooth shape of the distribution function resulting from the diffusion equation (or any transport equation) says nothing about the structures that may exist on scales shorter than the typical displacement X_c. This X_c is the intrinsic uncertainty of the transport equation in the transverse direction. Finer transverse scales are not described by the diffusion (transport) equation. Thus, contrary to the claim of Zurbuchen et al. [7], the fact that sharp gradients or small-scale solar features persist in the solar wind up to 1 AU and beyond cannot confirm or contradict the diffusivity of the magnetic field lines in the solar wind. To understand the presence of such gradients or the gradients observed by Mazur et al. [2], the transport must be described on scales fine enough that the typical intrinsic uncertainty of the description does not exceed the scale size of the gradients. For this a higher frequency part of the turbulence spectrum must be included in the description, which is done in Fig. 1b for shorter and shorter length scales (larger n).

The distributions calculated on any given scale are *statistical* in nature. Substructures may exist on the scales finer than those described by a smooth distribution. Only the superposition of all these finer substructures gives, statistically, the smoothness of the distribution observed on a larger scale, but the spacecraft observations on short time scales are *not* statistical. The spacecraft enters a magnetic flux tube at one point. Observations at the border of a magnetic flux tube are not averages of the shape of the profile over the whole periphery of the flux tube. This is always true whenever a new substructure of the magnetic field is encountered. The local measurements therefore detect more irregularities than the statistical distribution would seem to predict.

To learn about the size and sharpness of the substructures that may be encountered by the spacecraft, we assume the presence of very fine bundles of field lines and see how they evolve on each length scale. One interesting feature of the resulting distributions in Fig. 1b is that due to the very strong supradiffusion of the field lines on the short scales there is practically no overlap between successive distributions. The spreading on the shorter length scale is such that several sets of field lines would easily fit within the space covered by the distribution obtained on the next larger length scale. Since two successive length scales are separated by only a factor 2 in Fig. 1b, this is indicative of an extremely structured magnetic field and "self-similarity," with gradients becoming increasingly sharp as one increases the temporal resolution of the observations. The smallest scale size of the magnetic structures depends on the magnetic turbulence spectrum of the solar wind. Sizes of the finest filamentary structures ($0.4 - 1.5\,\mathrm{s}$ extrapolated to 1 AU) [6] may be well below the resolution limit of the current ACE observations, and the scale spectrum of magnetic substructures observable *via* the variations of particle intensity profiles may extend continuously down to the cutoff implied by particle cross-field scattering. This cutoff will be determined by the temporal resolution where the intensity profiles become energy dependent.

In summary, we have shown that the sharp gradients observed in the intensity profiles of impulsive particle events exist only because of the very strong supradiffusion of the field lines on the short and medium scales, due to the steep spectrum of magnetic turbulence measured on these scales. We also argued that these intermediate scales of magnetic turbulence may produce the substructures observed by Mazur et al. [2] within the larger channels.

4. References

1. Giacalone J., Jokipii J.R., Mazur J.E. 2000, ApJ 532, L75
2. Mazur J.E., et al. 2000, ApJ 532, L79
3. Ragot B.R. 1999, ApJ 525, 524
4. Ragot B.R. 2001a, ApJ 547, 1010
5. Ragot B.R. 2001b, Proc. 27th ICRC, 3293
6. Woo R, Habbal S.R. 1997, ApJ 474, L139
7. Zurbuchen T.H., et al. 2000, JGR 105, 18327