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Superdiffusive and ballistic propagation of protons in solar energetic particle events

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Abstract. In this work we show that protons can exhibit both superdiffusive and ballistic propagation, at variance with standard diffusion. We carry out an analysis of impulsive solar energetic particle (SEP) events, for which the observed time profile of energetic particle fluxes represent the propagator of the corresponding transport equation. We show that in the case of superdiffusive or ballistic transport the propagator in the time asymptotic regime has a power law form, and that a fit of the observed time profiles allows to determine the transport regime. Using data obtained from ACE and SoHO spacecraft, two proton and electron events, which exhibit both superdiffusive and ballistic transport, will be shown. The finding of these anomalous regimes implies that no finite mean free path can be defined.

1. Introduction

The solar corona is a powerful particle accelerator, being able to accelerate ions to energies of the order of 1 GeV, and electrons to energies of the order of tens of MeV. These particles escape the coronal plasma and propagate in the solar wind along the spiral magnetic field.In order to find anomalous transport regimes, i.e., superdiffusive- and ballistic regimes, we carry out an analysis of impulsive solar energetic particle(SEP) events. We selected events from SOHO and ACE data set (e.g. Krucker & Lin, 2000) where it is possible to assume that the energetic particles fluxesare accelerated in impulsive events like a flare. The characterization of the impulsive events follows the criteria proposedby Reames (1999): Intensity-time profiles of electrons and protons with a prevalenceof electron intensity and a duration of tens of hours; 3He-rich events. In the case of super diffusive or ballistic transport the propagator in thetime asymptotic regime has a power law form (Zumofen & Klafter, 1993; Metzler & Klafter, 2000) and a fit of the observed time profilesallows to determine the transport regime.

2. Impulsive events data and transport analysis

The transport analysis assumes that the impulsive events correspond to an injection of particles localized in space and time, so the transport of particles is described by the shape of the propagator. The propagator form related to super diffusive transport is used (Zumofen & Klafter, 1993 Perri & Zimbardo, 2007; Perri & Zimbardo, 2008), in particular its form calculated in real space in the approximation of long times:

$P(x,t) \sim a_0 / \left[(t)^{1/(\mu-1)}\right]$ which corresponds to the diffusion law $\langle \Delta x^2(t) \rangle \simeq 2D_\alpha t^\alpha$ with $\alpha = 4 - \mu$. In the case of transport in 3-D, assuming normal diffusion in the directions perpendicular to the magnetic field, the long time propagator scales as (Trotta & Zimbardo in progress)

$$P(t-t') \simeq \frac{N_0}{(t-t')^{\mu/(\mu-1)}} \tag{2.1}$$

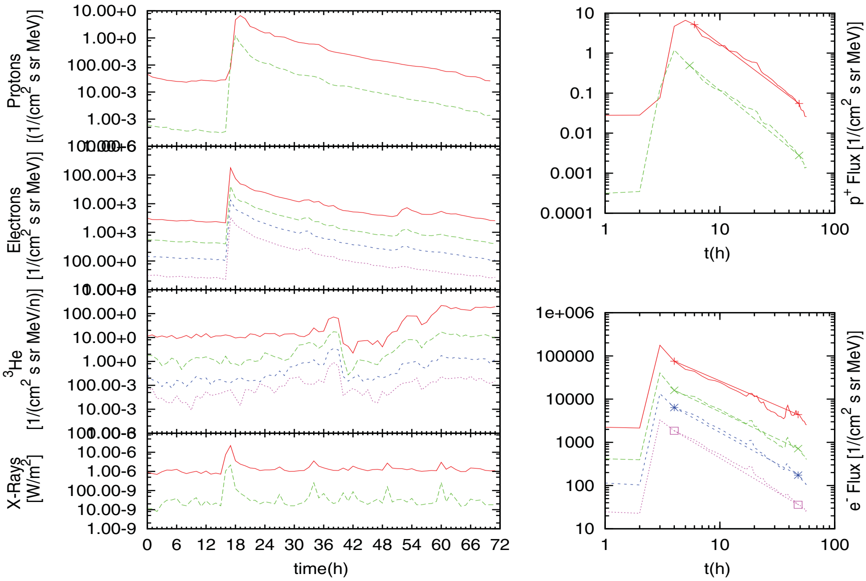

Figure 1. 2000 June 10 impulsive event. Lin-log graph of fluxes data. On the left from top to bottom: proton flux from SOHO, electron flux from ACE/EPAM, ^3He flux from ACE/ULEIS and X-Rays from GOES/SEM. On the right protons (top) and electrons (bottom) fit

The value of μ can be determinate using linear fit in log-log scale with slope give by $m = \mu/(\mu - 1)$: different values of μ identify different transport regimes:normal diffusion for $\mu > 3$, super diffusive transport for $2 < \mu < 3$, and ballistic (e.g. scatter-free) for $\mu < 2$.

Table 1. Summary of 2000 June 10 impulsive event

Data	$E_{max}(MeV)$	Satellite	Duration (h)	m	μ	χ^2	α	Flare-coords
Protons	16.40	SOHO	50.00	-2.12	1.89	0.20	2.00	N22W38
	33.00	SOHO	50.00	-2.28	1.78	0.22	2.00	
Electrons	0.05	ACE	50,00	-1,18	6.70	0.36	1.00	N22W38
	0.10	ACE	50.00	-1.34	3.96	0.24	1.00	
	0.18	ACE	50.00	-1.51	2.94	0.12	1.06	
	0.32	ACE	50.00	-1.62	2.61	0.09	1.39	

The flare is shown by the peak present in X-rays, that is also synchronized with the peak flux of protons and electrons. This allows us to characterize the event as impulsive event (Reames, 1999).The slope and the calculation of the exponent in transport equation, indicates ballistic (e.g. scatter-free) transport for protons (Fig. 1, Tab.1) and a superdiffusive transport for electrons. Table 1 also gives the energy channels, the duration of the event, and the χ^2 of the fit, and the flare coordinates. The next event (Fig. 2) is characterized by the presence of different transport type for protons in different channels of energy. Electron transport is superdiffusive. As previous events, proton and electron fluxes are compared with ^3He flux and SXR to characterize the event as impulsive event. Even for this event, the slope and the calculation of the exponent μ, indicates superdiffusive transport for both electrons and protons (Fig. 2, Tab. 2).

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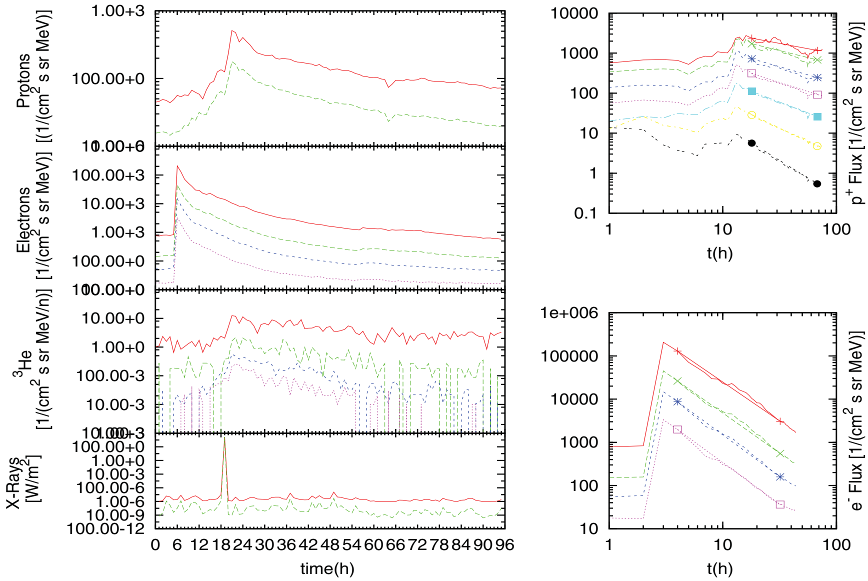

Figure 2. Same as Fig. 1, but for 2002 February 20 event

Table 2. Summary of 2002 February 20 impulsive event

Data	$E_{max}(MeV)$	Satellite	Duration (h)	m	μ	χ^2	α	Flare-coords
Protons	1.06	ACE	72.00	-1.05	21.00	0.03	1.00	N12W72
	1.91	ACE	72.00	-1.27	4.70	0.02	1.00	
	4.75	ACE	72.00	-1.66	2.52	0.03	1.48	
Electrons	0.05	ACE	52.00	-1.70	2.43	0.09	1.57	N12W72
	0.10	ACE	52.00	-1.81	2.23	0.07	1.77	
	0.18	ACE	52.00	-1.88	2.14	0.04	1.86	
	0.32	ACE	52.00	-1.85	2.18	0.03	1.82	

3. Conclusions

Using data obtained from ACE and SOHO spacecraft, we have shown that proton and electron events exhibit both superdiffusive and ballistic transport.These anomalous transport regime are important for the mechanisms of energetic particle acceleration and for space weather predictions.

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