Particle acceleration and heating in turbulent reconnecting astrophysical plasmas [1]

Loukas Vlahos, Heinz Isliker, Theothilos Pisokas and Anastasios Anastasiadis

July 12, 2017

[1] 13th Hellenic Astronomical Conference, Heraklion (Crete), 2-6 July 2017

Main Topics

- Define “Weak” and “Strong” turbulence and show that magnetic reconnection can be an element of strong turbulence (turbulent reconnection)
- Fermi acceleration inside strong turbulence
- Formation of strong turbulence environment during explosive events in the Sun and particle heating and acceleration during solar explosive events (Flares, CMEs)
- Discussion and Summary

Weak and Strong turbulence

A spectrum of MHD waves

$$\delta\vec{B} = \nabla \times \int \frac{d\vec{k}}{(2\pi)^3}[\vec{A}_k e^{-i(\omega(k)t - \vec{k}\cdot\vec{r} + \phi_k)}] \tag{1}$$

$$\vec{B} = \vec{B}_0 + \delta\vec{B} \tag{2}$$

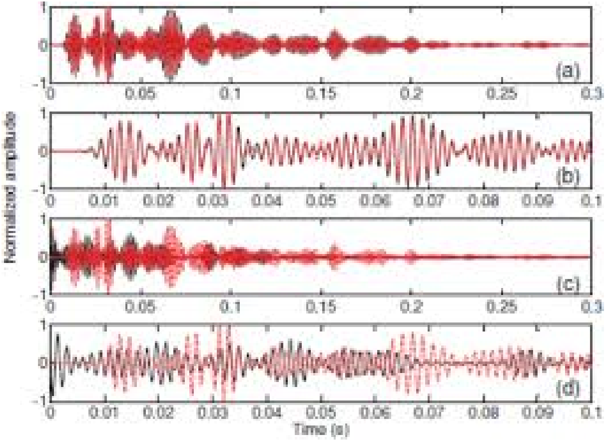
$$\vec{j} \approx \nabla \times \delta\vec{B} \tag{3}$$

$$\vec{E} = \eta\vec{J} + \frac{\vec{V} \times \vec{B}}{c} \tag{4}$$

Weak turbulence

$$\delta B/B_0 << 1 \quad (5)$$

Superposition of linear waves



Strong turbulence (Van Gogh)

$$\delta\rho/\rho_0 \approx 1 \tag{6}$$

Evolving the initial spectrum with resistive MHD equations

Based on a recent article by Isliker et al. Physical Review Letters, in press the 3D, resistive, compressible and normalized MHD equations used are

$$\partial_t \rho = -\nabla \cdot \mathbf{p} \tag{7}$$

$$\partial_t \mathbf{p} = -\nabla \cdot (\mathbf{pu} - \mathbf{BB}) - \nabla P - \nabla B^2/2 \tag{8}$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E} \tag{9}$$

$$\partial_t (S\rho) = -\nabla \cdot [S\rho\mathbf{u}] \tag{10}$$

with ρ the density, $\mathbf{p}$ the momentum density, $\mathbf{u} = \mathbf{p}/\rho$, P the thermal pressure, $\mathbf{B}$ the magnetic field, $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta\mathbf{J}$ the electric field, $\mathbf{J} = \nabla \times \mathbf{B}$ the current density, η the resistivity, $S = P/\rho^\Gamma$ the entropy, and $\Gamma = 5/3$ the adiabatic index.

The relativistic guiding center equations (without collisions) are for the evolution of the position $\mathbf{r}$ and the parallel component $u_{||}$ of the relativistic 4-velocity of the particles,

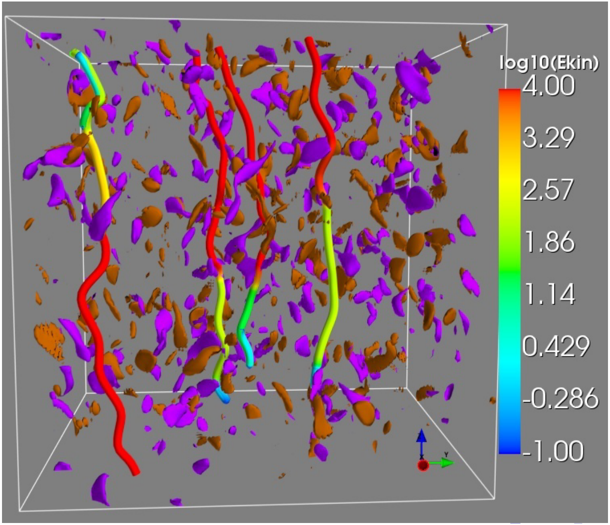
$$\frac{d\mathbf{r}}{dt} = \frac{1}{B_{||}^*}\left[\frac{u_{||}}{\gamma}\mathbf{B}^* + \hat{\mathbf{b}} \times \left(\frac{\mu}{q\gamma}\nabla B - \mathbf{E}^*\right)\right] \tag{11}$$

$$\frac{du_{||}}{dt} = -\frac{q}{m_0 B_{||}^*}\mathbf{B}^* \cdot \left(\frac{\mu}{q\gamma}\nabla B - \mathbf{E}^*\right) \tag{12}$$

where $\mathbf{B}^* = \mathbf{B} + \frac{m_0}{q}u_{||}\nabla \times \hat{\mathbf{b}}$, $\mathbf{E}^* = \mathbf{E} - \frac{m_0}{q}u_{||}\frac{\partial \hat{\mathbf{b}}}{\partial t}$, $\mu = \frac{m_0 u_\perp^2}{2B}$ is the magnetic moment, $\gamma = \sqrt{1 + \frac{u^2}{c^2}}$, $B = |\mathbf{B}|$, $\hat{\mathbf{b}} = \mathbf{B}/B$, $u_\perp$ is the perpendicular component of the relativistic 4-velocity, and q, m_0 are the particle charge and rest-mass, respectively.

Strong turbulence

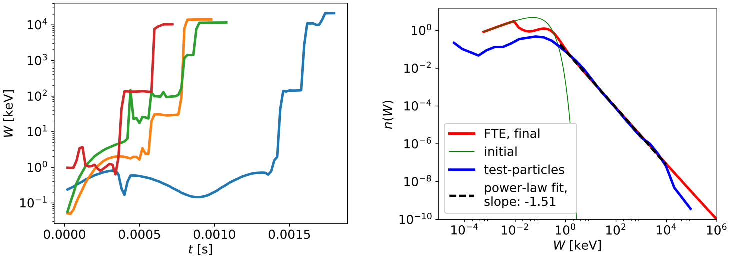
$$\delta B / B_0 = 1 \tag{13}$$



Strong turbulence

(14)

Typical orbits and the energy distribution



Particle transport in strong turbulent plasmas

The main tool for the analysis of the energy transport of particles is the Fokker Planck equation

$$\frac{\partial f(W,t)}{\partial t} = \frac{\partial [F_W(W) f(W,t)]}{\partial W} + \frac{\partial^2 [D_{WW}(W) f(W,t)]}{\partial W^2} - \frac{f(W,t)}{t_{esc}} \quad (15)$$

transport coefficients

$F_W(W) = < dW/dt >$ convection

$D_{WW}(W) = \frac{<(W(t+\Delta t) - W(t))^2>}{2\Delta t}$ diffusion

t_{esc} characteristic escape time

Particle transport in strong turbulent plasmas

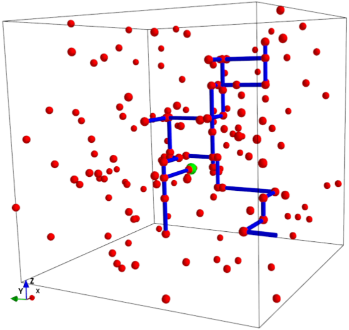
Important questions:

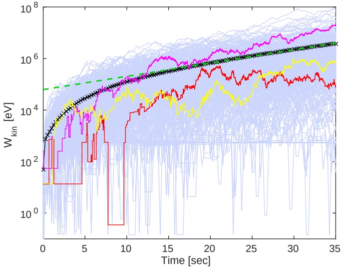
- In weak turbulence the transport coefficients F_W, D_{WW} are estimated analytically from the Quasiliner approximation.
- In strong turbulence, we have no way to estimate them and on top of that we have no way to prove that the FP equation is valid.

How far can we go by using the initial ideas of Fermi

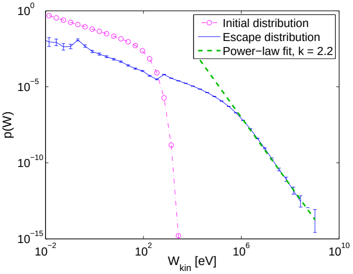
The strong turbulent environment can be modeled in line with the initial idea of Fermi, where the strong scatterers can replace the "magnetic clouds" and the particles gain energy stochastically (second order Fermi) Pisokas et al. ApJ 2017

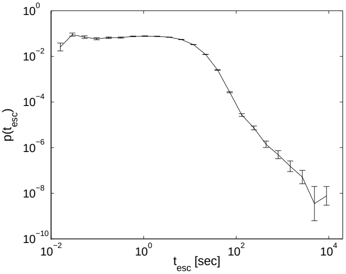
$$\Delta W = \frac{2}{c^2}(V_A^2 - \vec{V_A} \cdot \vec{u})W$$





In 10-15 secs the plasma has been heated and the tail has been accelerated to very high energies stochastically. The mean escape time from the box is approximately equal with the acceleration time (around 10secs) and the power law reaches asymptotically an index around 2!

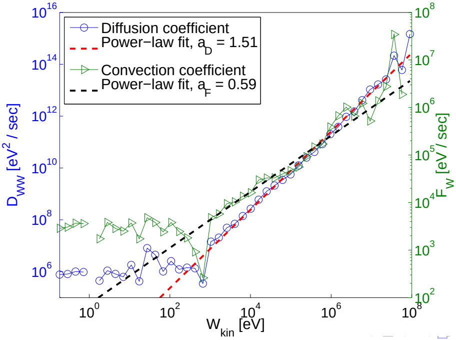




How we will estimate the transport coefficients?
We use the orbits and the formulae

$$D_{WW}(W) = \frac{< (W(t+\Delta t) - W(t))^2 >_W}{2\Delta t}$$

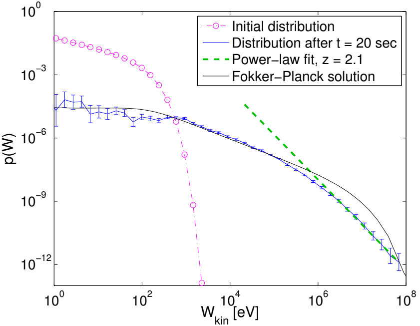
$$F_W(W) = \frac{< W(t+\Delta t) - W(t) >_W}{\Delta t}$$



Energy transport for the stochastic Fermi acceleration

Using the transport coefficients and the estimated mean escape time we solve the transport equation

$$\frac{\partial f(W,t)}{\partial t} = \frac{\partial [F_W(W) f(W,t)]}{\partial W} + \frac{\partial^2 [D_{WW}(W) f(W,t)]}{\partial W^2} - \frac{f(W,t)}{t_{esc}} \quad (16)$$

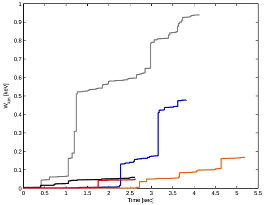


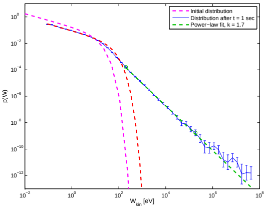
How far can we go by using the initial ideas of Fermi

Vlahos et al. Apj Letters 2016, Isliker et al. (in preparation)

The strong turbulent environment can be modeled in line with the initial idea of Fermi, where the Reconnecting Current Sheets can replace the "magnetic clouds" and the particles gain energy systematically (First order Fermi)

$$\Delta W = \mid q \mid E_{eff} \ell_{eff}$$

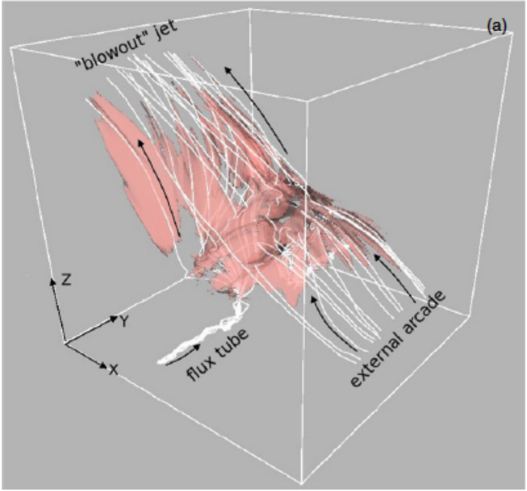




The most important finding in this study is the failure of the FP equation to reproduce the test particle results of a systematic accelerator

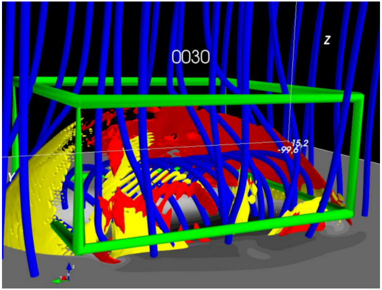
Formation of strong turbulence environment during explosive events in the Sun

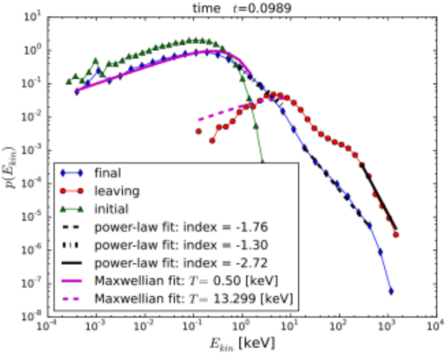
Archontis and Hood in ApJ Letters (2013)



Formation of strong turbulence environment during explosive events in the Sun

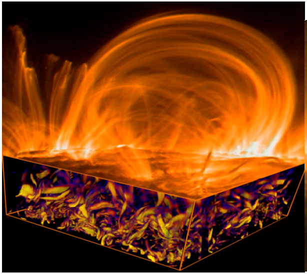
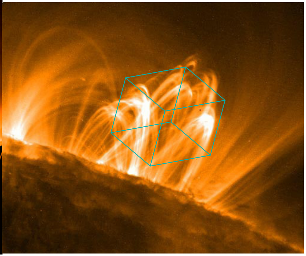
Isliker, Archontis and Vlahos (in preparation)





Summary and discussion

The magnetic field in the solar corona is always under stress from the driver (convection zone)

- The solar corona is always in a (weak or strong) turbulent state.
- Explosive phenomena add complexity to the magnetic filed, current fragmentation and turbulent reconnection on large scale topologies.
- Heating and particle acceleration naturally sets in, in this strong turbulent environment.