Turbulence and standard model of solar flares


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**Solar flares** are rapid localised brightening in the lower atmosphere.

More prominent in X-rays, UV/EUV and radio…. but can be seen from radio to 100 MeV

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*Figure from Krucker et al, 2007*
Standard model energetics

- Magnetic Energy
- Turbulence/Fluctuating E fields
- Acceleration/Heating
  - Electrons/ions
  - Energy Deposition/Evaporation
  - Radiation

Petrosian (2012) cartoon
Typical solar flare: X-ray prospective

Using imaging spectroscopy, we can infer spectra and numbers of energetic electrons both in coronal and footpoints sources.

Above 30 keV, we have normally a few times electrons more in the LT than in FP source. Possible trapping by waves or mirror?
**Stochastic particle acceleration**
Vast literature exists e.g. Miller et al, 1997; Petrosian 2012; Bian et al, 2012 Cargill et al, 2012 as reviews
⇒ Generally efficient electron and proton acceleration, He3 enhancement, variety and variability of particle spectra

**Particle and energy transport**
Pitch angle scattering of particles, reduced thermal conductivity, etc
⇒ Artificial injection of electrons often involved to explain strong radio sources at the loop-tops (e.g. Melnikov et al 2001, Lee et al, 2002)

**Reconnection models**
Anomalous resistivity is often required to make fast reconnection and strong parallel electric fields
see e.g. Priest and Forbes, 2002, Zharkova et al, 2012, Raymond et al, 2012 as recent reviews

Plasma turbulence is characterised by chaotic and stochastic property changes, e.g. velocity, density, magnetic field in space and time.
Motivation

**Stochastic particle acceleration**
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**Particle and energy transport**
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⇒ Artificial injection of electrons often involved to explain strong radio sources at the loop-tops
⇒ (e.g. Melnikov et al 2001, Lee et al, 2002,
⇒ Simoes & Kontar 2013, Kontar et al, 2014)

**Reconnection models**
Anomalous resistivity is often required to make fast reconnection and strong parallel electric fields
see e.g. Lazarian et al, 1999, Raymond et al, 2012, Gordovskyy et al,2016
Plasma turbulence is characterised by chaotic and stochastic property changes, velocity, density, magnetic field in space and time.
SDO/Atmospheric Imaging Assembly (AIA) 193 Å image (background); RHESSI x-ray contours at 50% of peak value for 6–15 (red) and 25–50 keV (blue) energy ranges, EIS Fe XXIV (255 Å) intensity map (white contours at 30% and 75% of peak value), and Nobeyama 34 GHz radio emission (green contours at 30% and 75% of peak value).

From Kontar et al, PRL, 2017
Measurements for flare energetics

- **Magnetic Energy**
  - SDO/HMI - Magnetic field reconstruction and radio emission
  - Spatially resolved velocity fluctuations from EIS

- **Turbulence/Fluctuating E fields**
  - SDO/AIA – thermal plasma

- **Acceleration/Heating**
  - RHESSI and “warm target” electrons energetics

- **Electrons/Ions**
  - Energy Deposition/Evaporation

- **Radiation**
Electron energetics
Non-thermal line broadening

EIS Line width (Fe XXIV) => plasma velocity variance

See Harra et al 2013 for details

e.g. non-thermal line broadening observed in flares, normally spatially unresolved, but now with Hinode/EIS – spatially resolved
Magnetic field

SDO HMI extrapolations

\[ U_m = \frac{B^2 L^3}{8\pi} \]
Flare energetics
Turbulence dissipation timescale $\sim L_\perp / v_{nth}$. 

The energy density associated with a turbulence-perturbed magnetic field $\delta B$ is $U_B \approx (\delta B)^2 / 8\pi$. Equating this to the turbulent energy content (Alfvénic MHD turbulence) $K = (1/2)n m \langle v_{nth}^2 \rangle$, we obtain $\langle v_{nth}^2 \rangle \approx (\delta B)^2 / 4\pi n m$. Since the Alfvén speed $V_A = \sqrt{B^2 / 4\pi n m}$, it follows that $\langle v_{nth} \rangle / V_A \approx \delta B / B \approx L_\perp / L_\parallel$, where $L_\parallel$ is the longitudinal extent of the turbulence region. Thus the dissipation timescale $L_\perp / \langle v_{nth} \rangle$ is approximately the same as the Alfvén crossing time $L_\parallel / V_A$, a quantity that is readily ascertainable from observations. Using the values found in the observations, the dissipation of turbulent energy occurs on a time scale $\sim 1 - 10$ seconds.
Standard model energetics

Magnetic Energy \(\sim 10^{31} \text{ ergs}\)

Turbulence \(\sim 10^{28} \text{ ergs}\)

Electron Acceleration \(\sim 10^{28} \text{ erg/sec}\)

Thermal energy \(\sim 10^{30} \text{ ergs}\)

Radiation
The new multiwavelength observations provide persuasive evidence that plasma turbulence plays a key role in the energy transfer in solar flares, thus directly supporting the stochastic acceleration model.

The turbulent kinetic energy (instantaneous) comprises only a small part of the total flare energy budget (~0.2-1%). Nevertheless, provided that its energization and dissipation processes are rapid enough (with the timescales of ~1-10 s),

The energy dissipation rate and the power in accelerated nonthermal particles observed in the flare are consistent with the dissipation of anisotropic Alfvén MHD turbulence.

The observations could be used to test various acceleration models.