Basic Processes of Turbulent Plasmas

Summer School
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Plasma-turbulence and wave-particle interaction downstream of the main interplanetary shock of the Bastille Day coronal mass ejections

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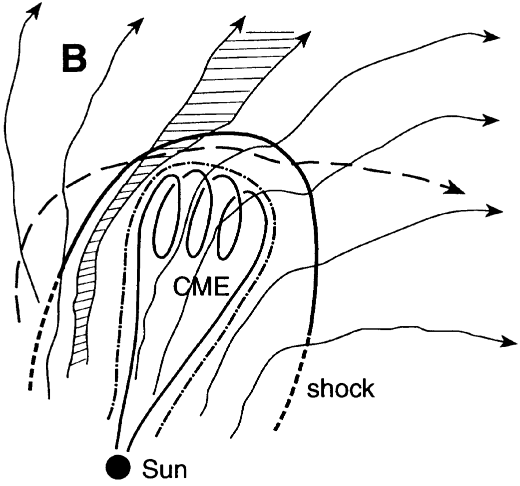
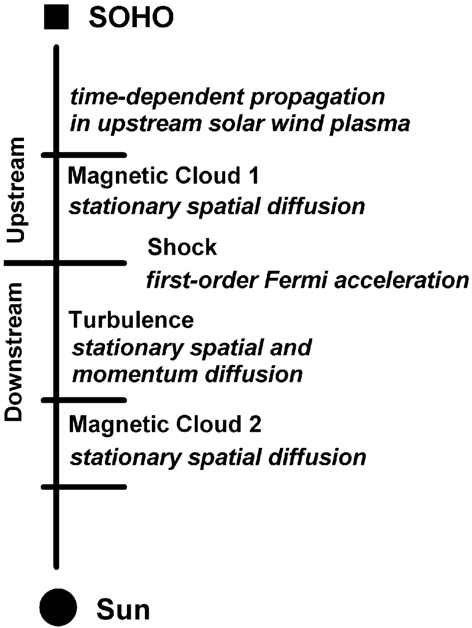
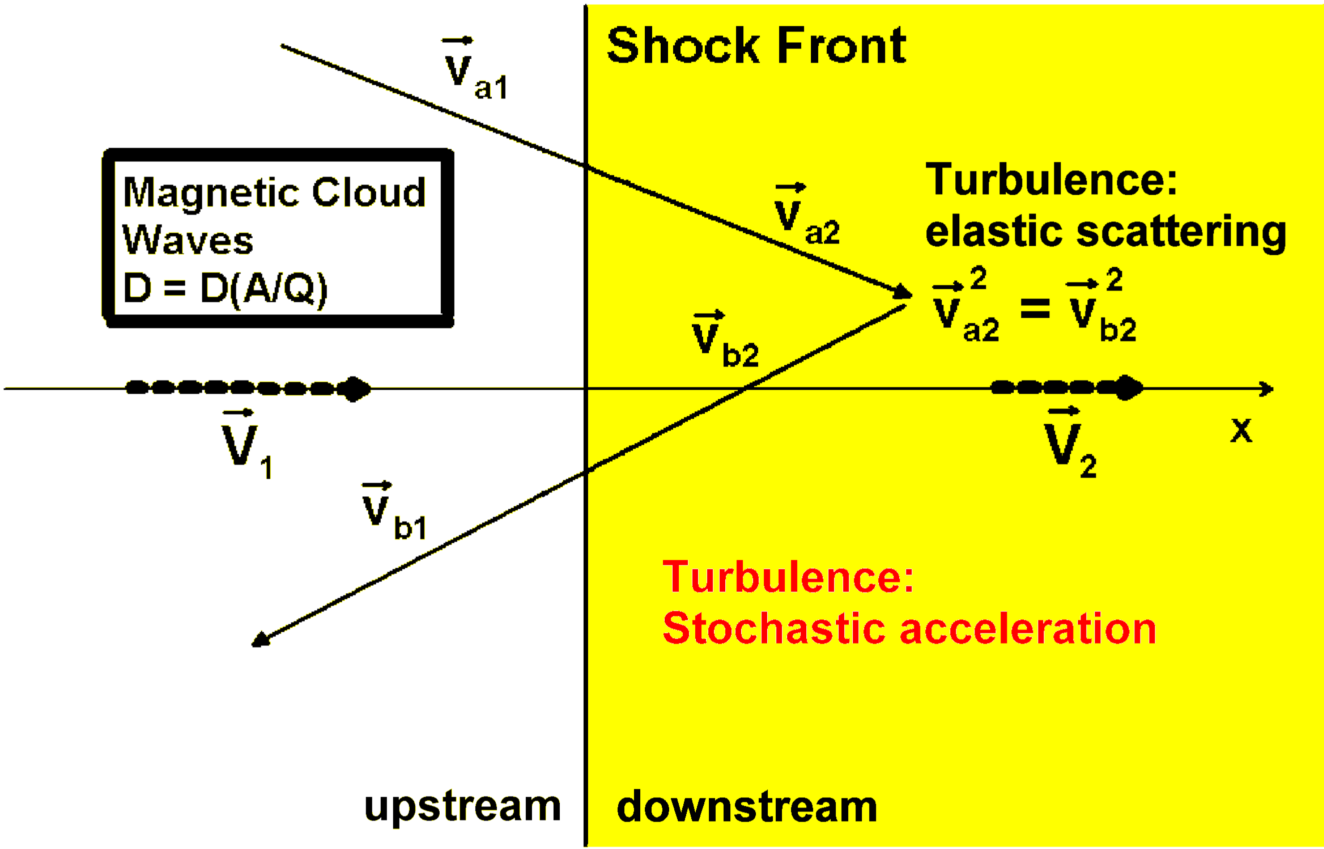
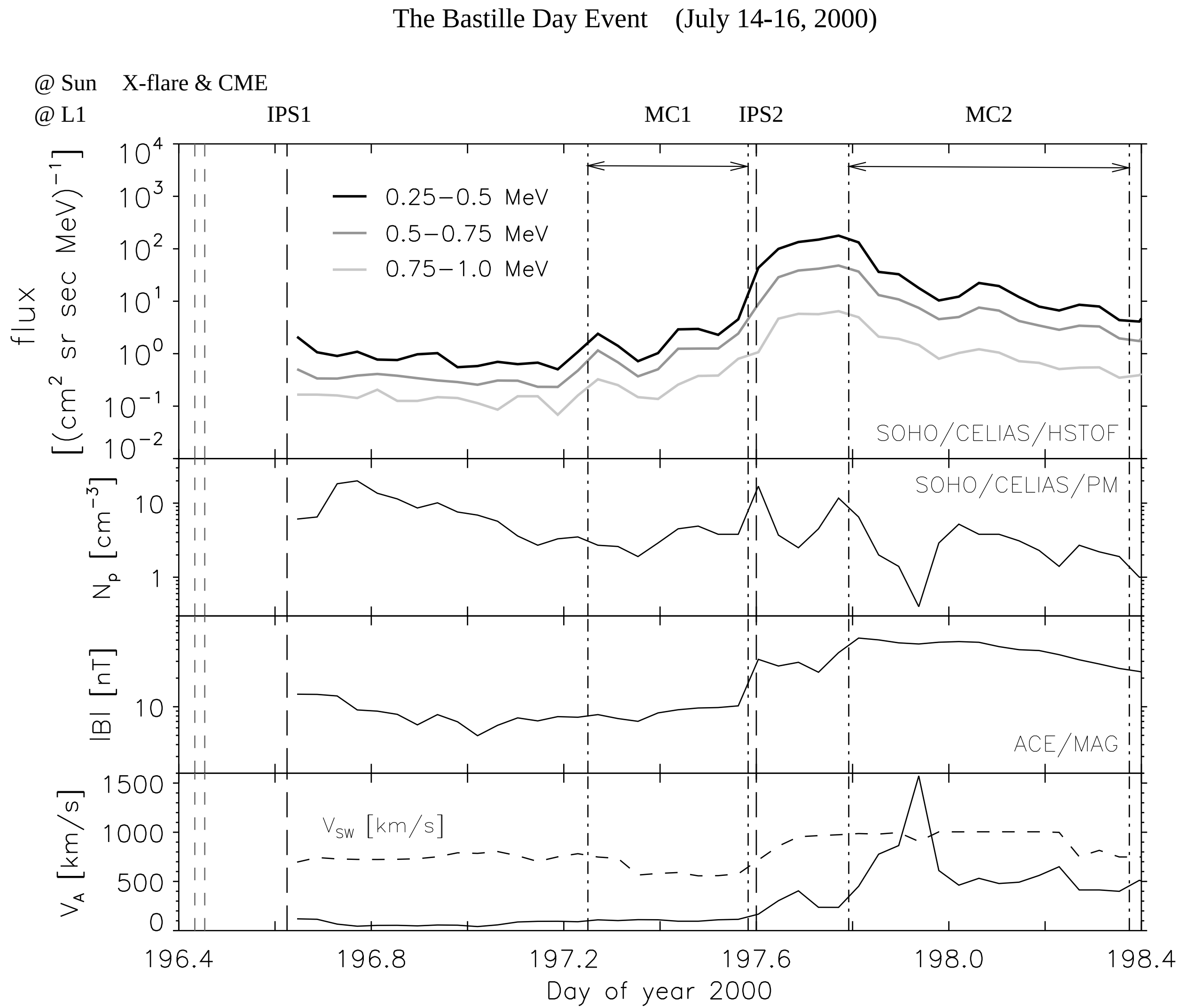


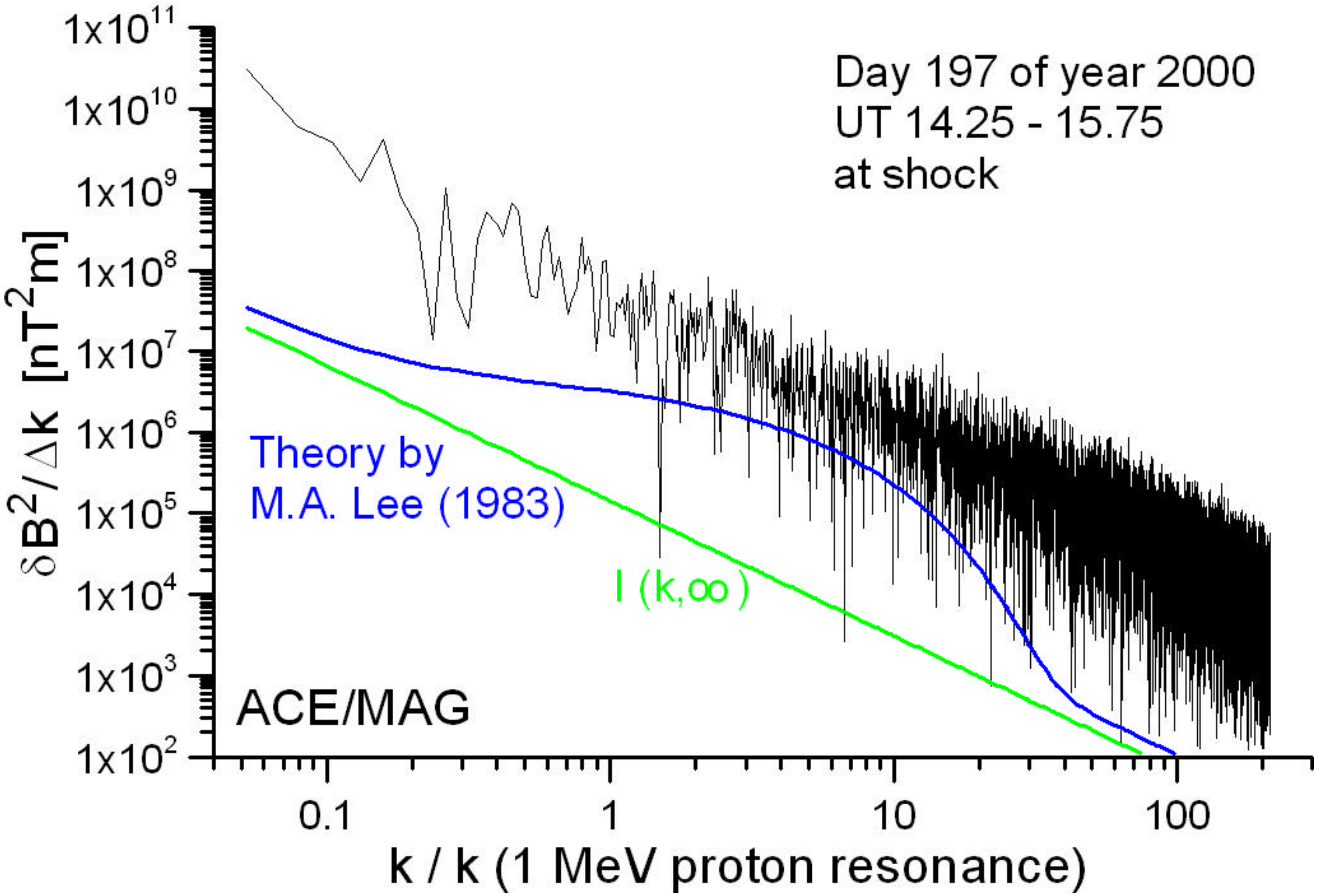
Configuration of a CME
(M.A. Lee, 1997)



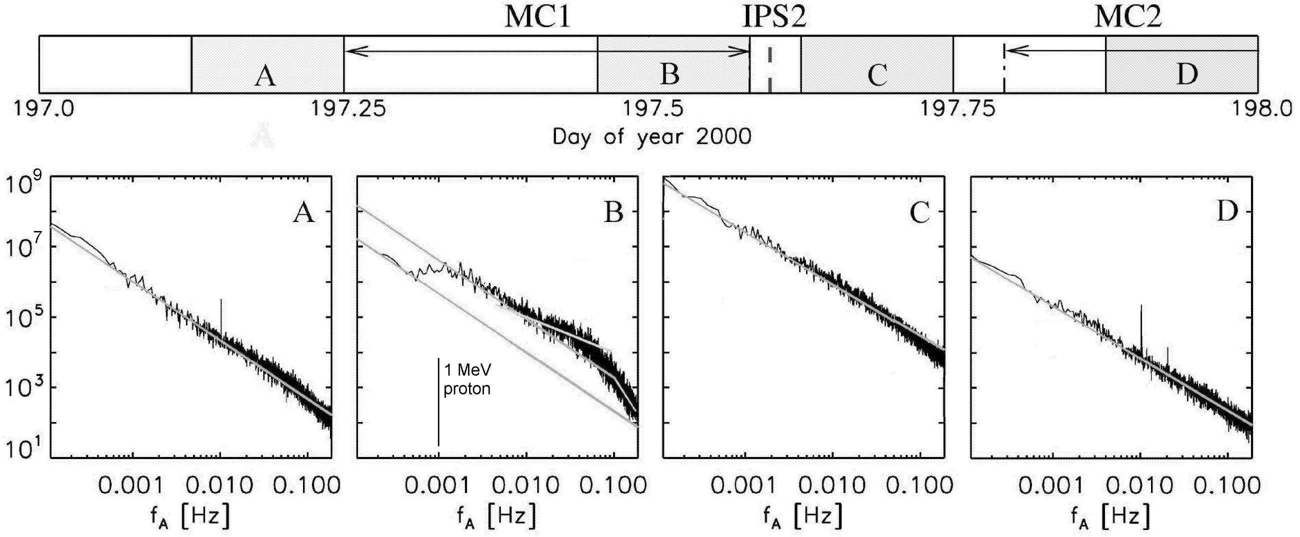


Shock Front
Magnetic Cloud
Waves
D = D(A/Q)
$\vec{v}_{a1}$
$\vec{v}_{a2}$
Turbulence:
elastic scattering
$\vec{v}_{a2}^{\,2} = \vec{v}_{b2}^{\,2}$
$\vec{v}_{b2}$
$\vec{V}_1$
$\vec{V}_2$
x
$\vec{v}_{b1}$
Turbulence:
Stochastic acceleration
upstream
downstream

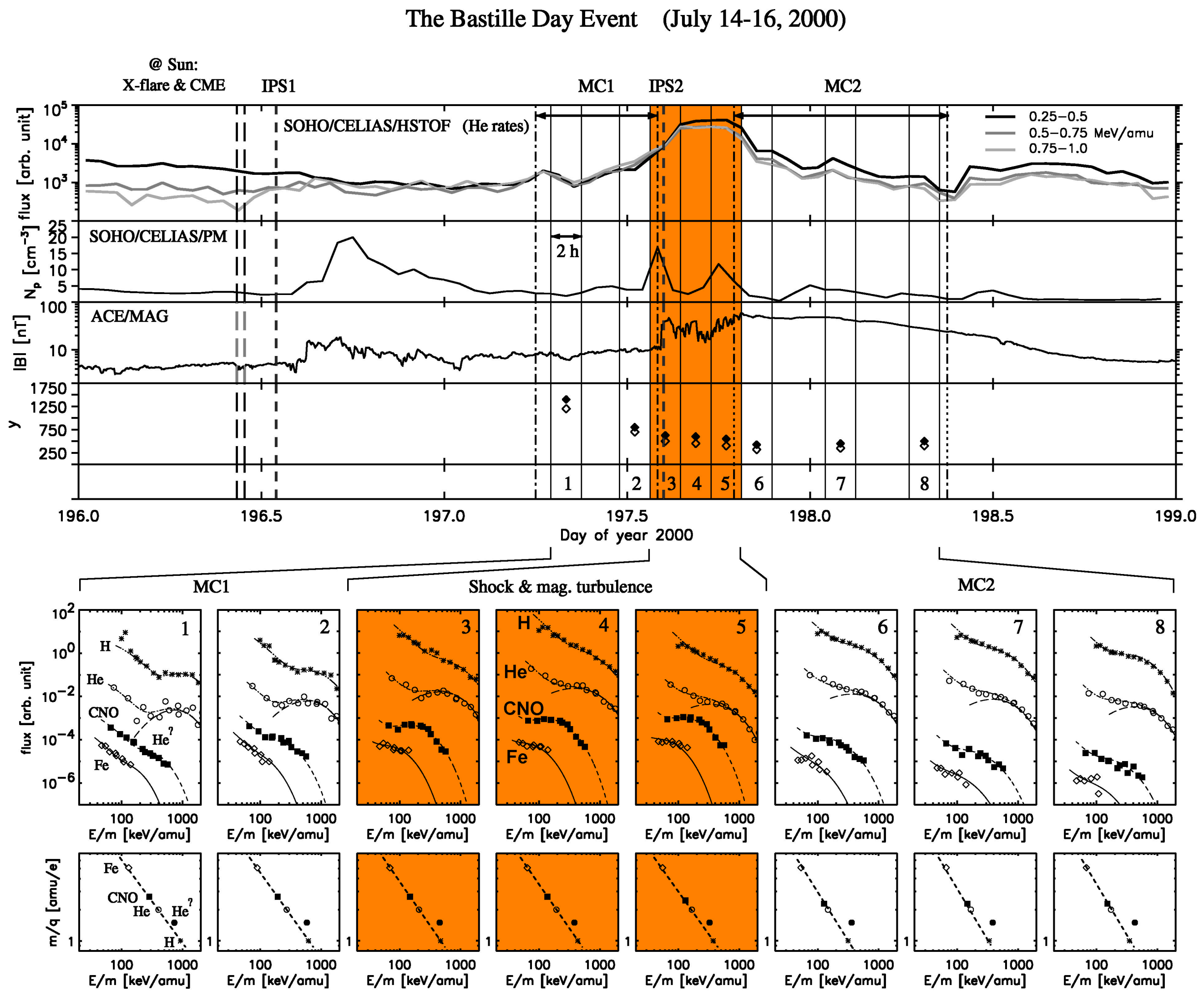

The Bastille Day Event (July 14-16, 2000)
@ Sun X-flare & CME
@ L1 IPS1 MC1 IPS2 MC2
0.25–0.5 MeV
0.5–0.75 MeV
0.75–1.0 MeV
flux [(cm2 sr sec MeV)−1]
SOHO/CELIAS/HSTOF
SOHO/CELIAS/PM
Np [cm−3]
|B| [nT]
ACE/MAG
VSW [km/s]
VA [km/s]
Day of year 2000



Day 197 of year 2000
UT 14.25 - 15.75
at shock
Theory by
M.A. Lee (1983)
I (k,∞)
ACE/MAG
δB²/Δk [nT²m]
1x10^11
1x10^10
1x10^9
1x10^8
1x10^7
1x10^6
1x10^5
1x10^4
1x10^3
1x10^2
0.1
1
10
100
k / k (1 MeV proton resonance)



MC1
IPS2
MC2
A
B
C
D
197.0
197.25
197.5
197.75
198.0
Day of year 2000
$\delta\tilde{B}^2$ [nT^2m]
10^9
10^7
10^5
10^3
10^1
1 MeV proton
0.001
0.010
0.100
f_A [Hz]


The Bastille Day Event (July 14-16, 2000)
@ Sun:
X-flare & CME
IPS1
MC1
IPS2
MC2
SOHO/CELIAS/HSTOF (He rates)
0.25–0.5
0.5–0.75 MeV/amu
0.75–1.0
flux [arb. unit]
SOHO/CELIAS/PM
2 h
N_p [cm^{-3}]
ACE/MAG
|B| [nT]
y
1 2 3 4 5 6 7 8
Day of year 2000
MC1
Shock & mag. turbulence
MC2
H
He
CNO
Fe
He?
flux [arb. unit]
E/m [keV/amu]
m/q [amu/e]

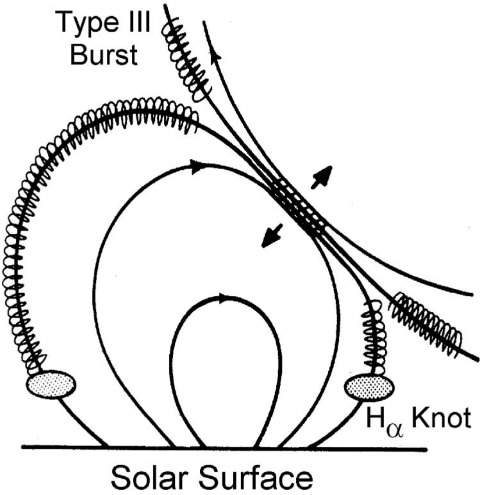


Figure 136. Erzeugung von Elektronenstrahlen oder Asymmetrien in der Elektronentemperatur ($T_{e\|} \gg T_{e\perp}$) durch die Rekonnexion in impulsiven Flares auf der Sonnenoberfläche.

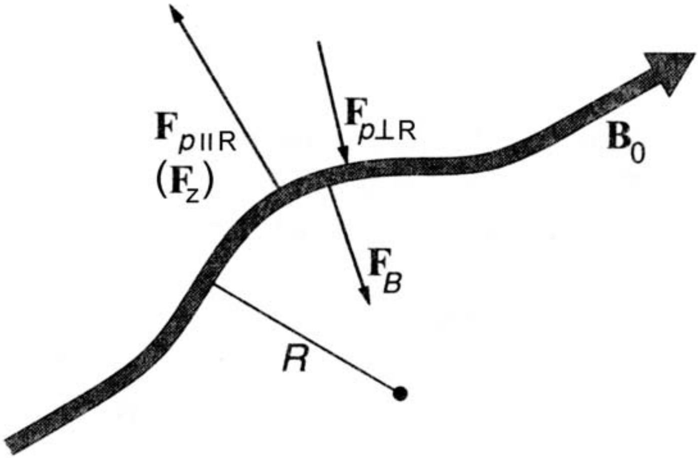
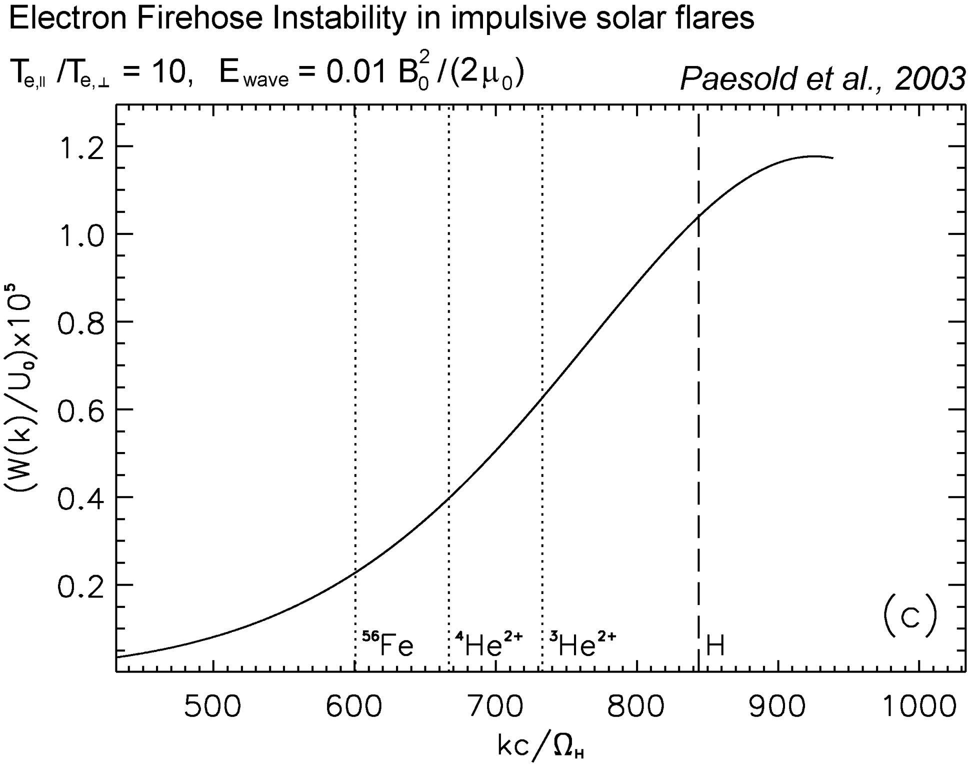


Figure 135. Schematische Darstellung der Feuerwehrschlauchinstabilität (Treumann and Baumjohann, 1997; Seite 51).



Electron Firehose Instability in impulsive solar flares
$T_{e,\parallel} / T_{e,\perp} = 10$, $E_{wave} = 0.01\, B_0^2 / (2\mu_0)$
Paesold et al., 2003
1.2
1.0
0.8
0.6
0.4
0.2
$(W(k)/U_0) \times 10^5$
^{56}Fe
$^{4}He^{2+}$
$^{3}He^{2+}$
H
(c)
500
600
700
800
900
1000
kc/Ω_H

cyclotron resonance

$$\xi = \Omega_{\mathrm{s}} + k_{\|} v_{\|} - \omega$$

$$v_{\perp} \dot{v}_{\perp} \approx \frac{2\pi q^2 E_{\mathrm{rms}}^2}{m^2 \delta\omega}$$

$$\frac{\dot{W}_{\perp}}{m} \approx 6.1 \left[\frac{\mathrm{Mev}}{\mathrm{amu\ s}} \right] \left(\frac{E_{\mathrm{rms}}}{100\ \mathrm{V\ m^{-1}}} \right)^2 \left(\frac{10^6 \mathrm{rad\ s^{-1}}}{\delta\omega} \right) \left(\frac{\mathrm{Q}}{\mathrm{A}} \right)^2$$

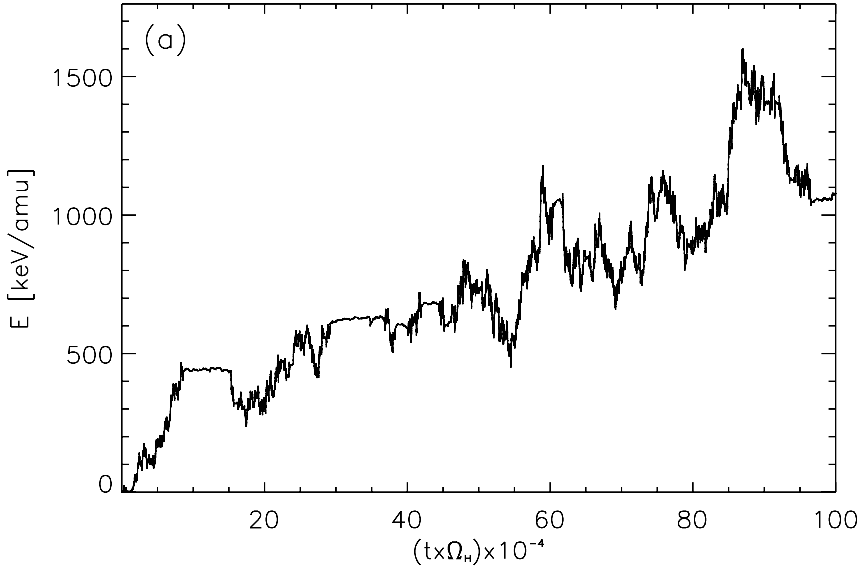
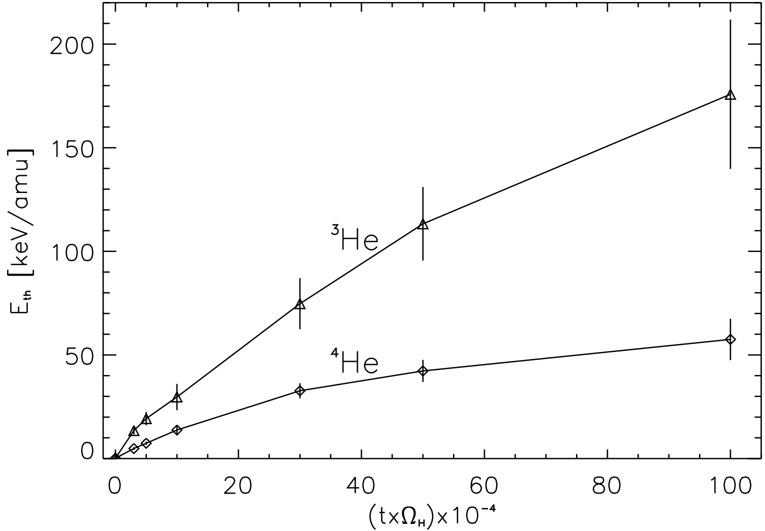
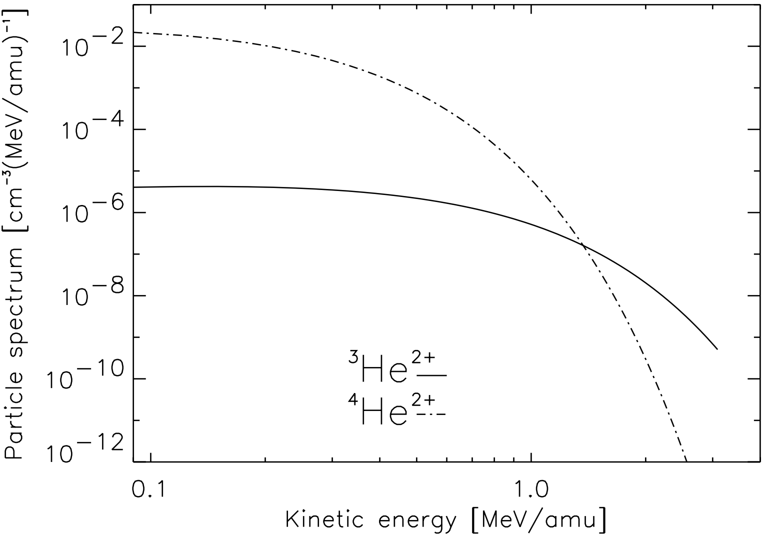


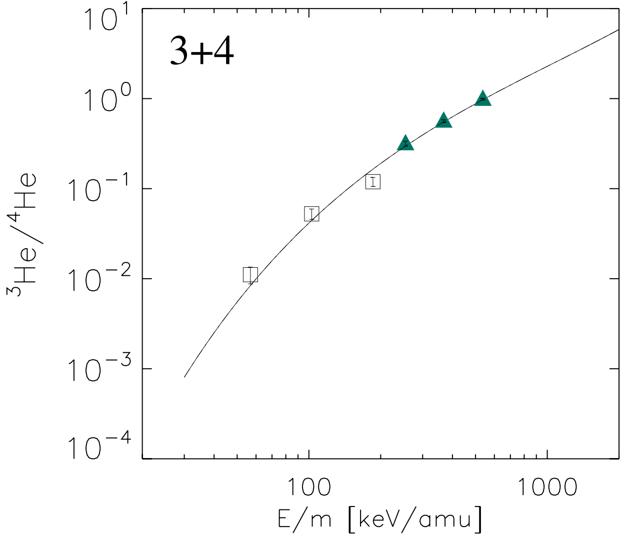
Figure 141. Zunahme der Gesamtenergie eines Ions mit der Zeit (von Paesold *et al.*, 2003).



E_{th} [keV/amu]
200
150
100
50
0
0
20
40
60
80
100
$(t \times \Omega_H) \times 10^{-4}$
^{3}He
^{4}He



Particle spectrum [cm⁻³(MeV/amu)⁻¹]
10−2
10−4
10−6
10−8
10−10
10−12
0.1
1.0
Kinetic energy [MeV/amu]
³He²⁺
⁴He²⁺



3+4
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$^3He/^4He$
100
1000
E/m [keV/amu]

Transport equation:

$$\frac{\partial f}{\partial t} + \mathbf{V} \cdot \nabla f = \nabla \cdot (\kappa \nabla f) + I - S + \frac{p}{3} \frac{\partial f}{\partial p} \nabla \cdot \mathbf{V} + \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial f}{\partial p} \right)$$

Roll-over of velocity distribution:

$$f\left(v\right) \propto \exp\left[-v^2/v_{\mathrm{ro}}^2\right] \ ,$$

$$v_{\mathrm{ro}}^2 \quad \approx \quad v_{\mathrm{1MeV}}^2 \ L_{\mathrm{turb}} k_{\mathrm{1MeV}}^2 \left(2-\alpha\right) \left(\frac{Q}{A}\right)^{2-\alpha} \frac{\delta\tilde{B}^2\left(k_{\mathrm{1MeV}}\right)}{B_0^2} \approx v_{\mathrm{1MeV}}^2 \ 0.01 \left(\frac{Q}{A}\right)^{2-\alpha} \left(2-\alpha\right)$$

$$\text{for} \quad L \approx 1.4 \times 10^{10} \ \mathrm{m} \ ; \ k_{\mathrm{1MeV}} \approx 1.4 \times 10^{-8} \mathrm{m}^{-1} \ ; \ \frac{\delta\tilde{B}^2\left(k_{\mathrm{1MeV}}\right)}{B_0^2} \approx 3 \times 10^5 \mathrm{m}$$

$-\alpha < 2$: spectral index power spectral density $\delta\tilde{B}^2(k)$

Momentum diffusion:

Quasi-linear theory, "1D" ;

$$D_{vv;1\mathrm{D}} = \pi \Omega_{\mathrm{s}}^2 v |\mu| \delta \tilde{B}^2(k_{\mathrm{res}})/B_0^2 \quad ;$$

2D-MHD (le Roux et al., 2002):

$$D_{vv;2\mathrm{D}} = \eta 2\pi^3 \Omega_{\mathrm{s}} \mu^2 v^2 V_{\mathrm{A}}^2 \langle \delta \tilde{B}_\perp^2 \rangle^2 / B_0^4 / V^2$$

μ: cosine of pitch-angle ; $\eta = r_{\mathrm{A}} - \frac{1}{4}\sigma_{\mathrm{c}}^2 \left(1 + r_{\mathrm{A}}\right)^2$ σ_{c}: cross-helicity ;
r_{A}: ratio spectral energy density of velocity fluctuations to magnetic field fluctuations

$$\begin{aligned} \frac{D_{vv;2\mathrm{D}}}{D_{vv;1\mathrm{D}}} &\approx \eta \left(L_{\mathrm{turb}} k\right)^{\alpha-1} = \eta \left(L_{\mathrm{turb}} k_{1\mathrm{MeV}}\right)^{\alpha-1} \left(\frac{k}{k_{1\mathrm{MeV}}}\right)^{\alpha-1} \\ &\approx 40\eta \left(\frac{k}{k_{1\mathrm{MeV}}}\right)^{2/3} \;;\; L_{\mathrm{turb}} \approx 1.4 \times 10^{10}\,\mathrm{m} \;;\;;\; k_{1\mathrm{MeV}} \approx 1.4 \times 10^{-8} \mathrm{m}^{-1} \;;\; \alpha = 5/3 \end{aligned}$$

Conclusions

- Second-order Fermi acceleration for super-Alfvénic particles in the heliosphere is important, if data of Bastille Day event are due to stochastic acceleration in downstream 2D-MHD turbulence.
- Energetic (suprathermal) particles are probes for plasma turbulence.
- Need a theory for sub-Alfvénic particles.