Basic Processes of Turbulent Plasmas

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Wave-particle interaction upstream of a CME-driven shock: SOHO/CELIAS/HSTOF and ACE/MAG data

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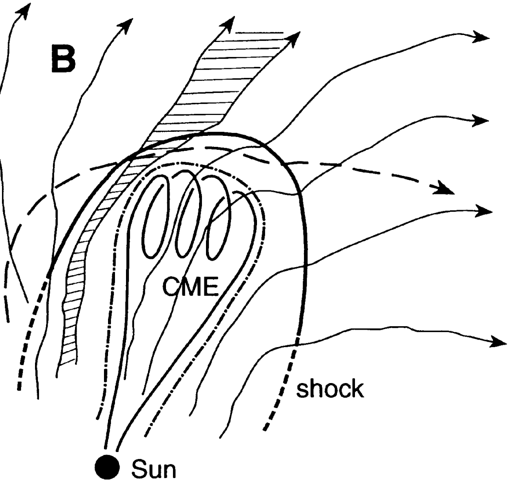
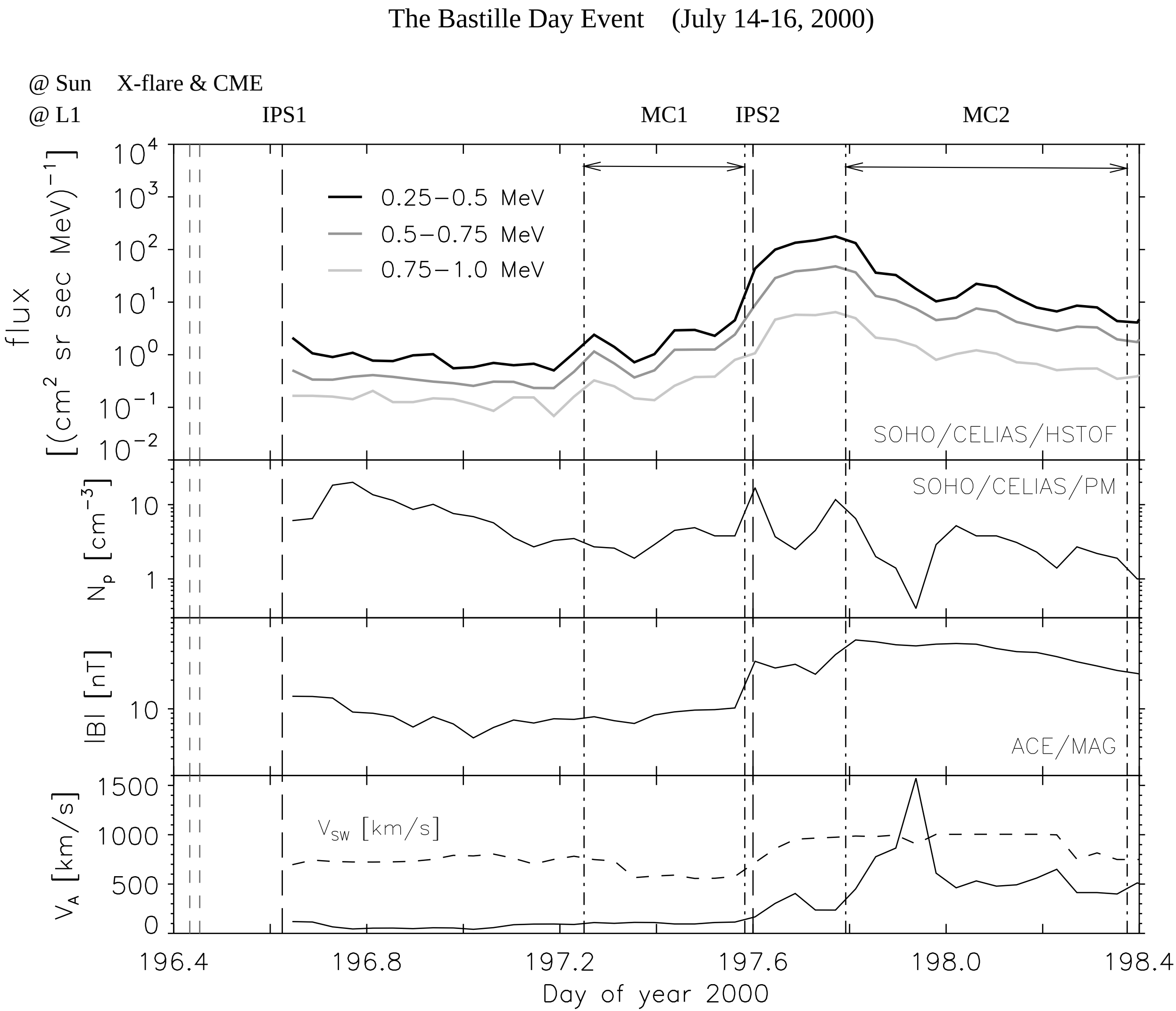
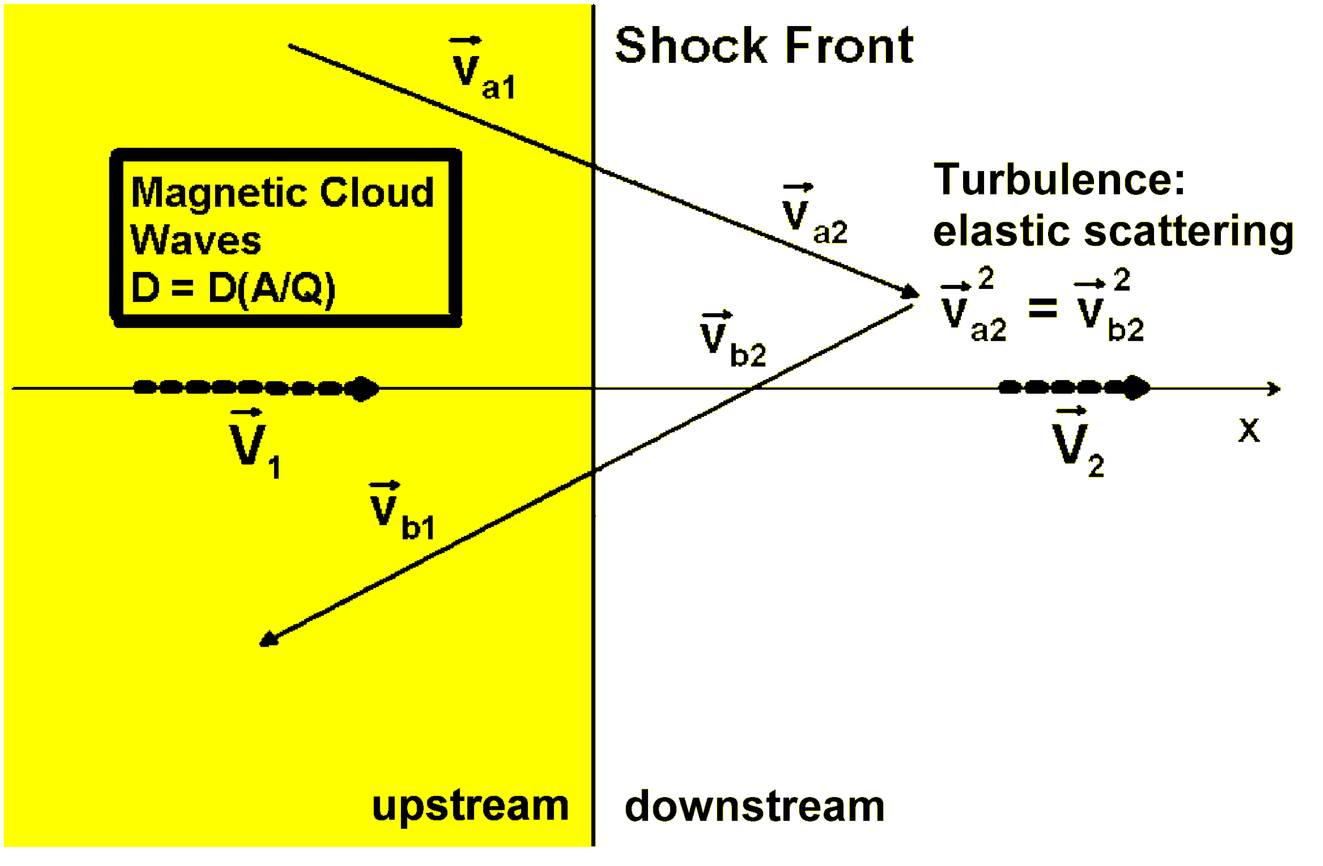


Configuration of a CME
(M.A. Lee, 1997)



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
VA [km/s]
VSW [km/s]
Day of year 2000


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

cyclotron resonance

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

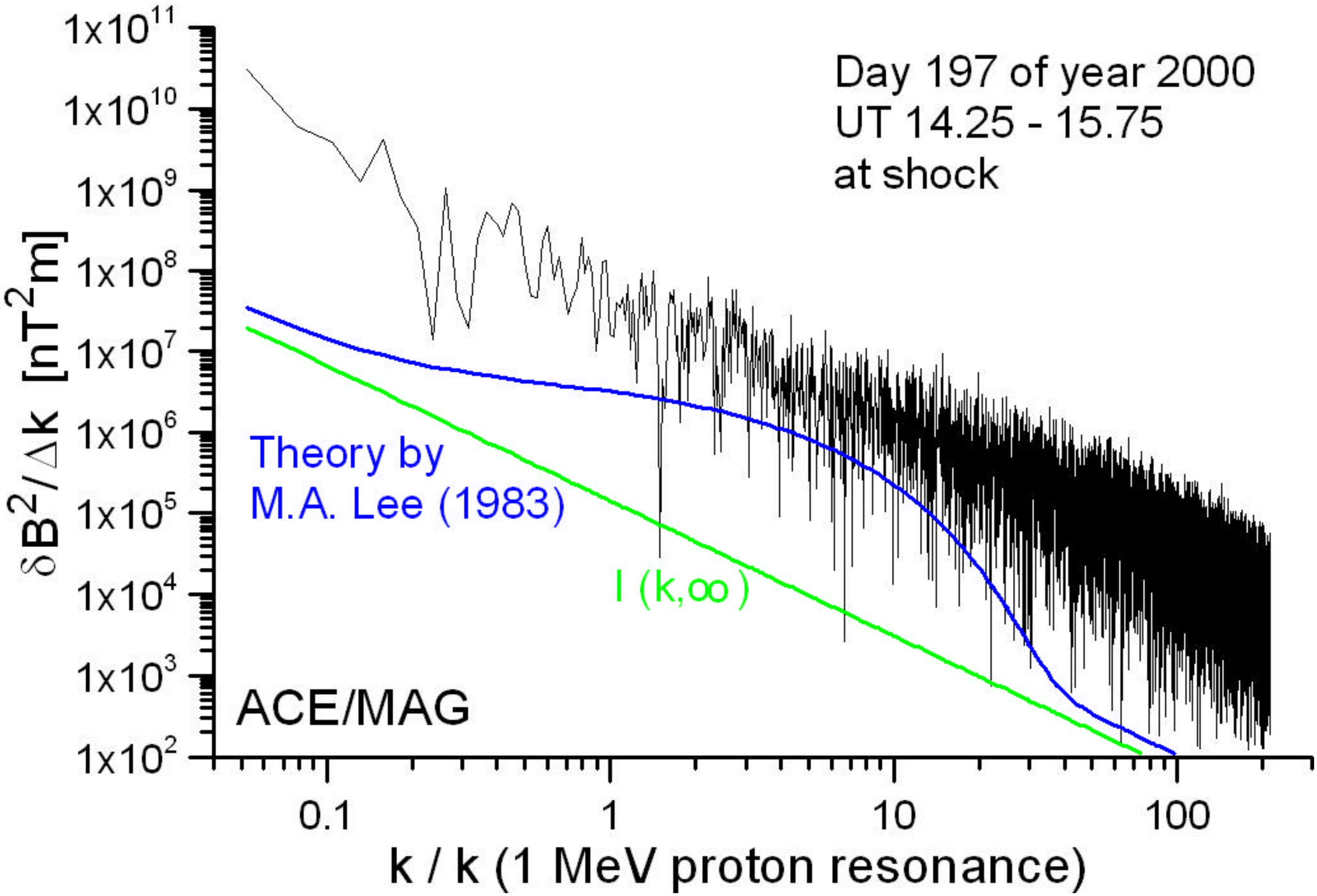
Lee (1983)

asymmetry in phase space density

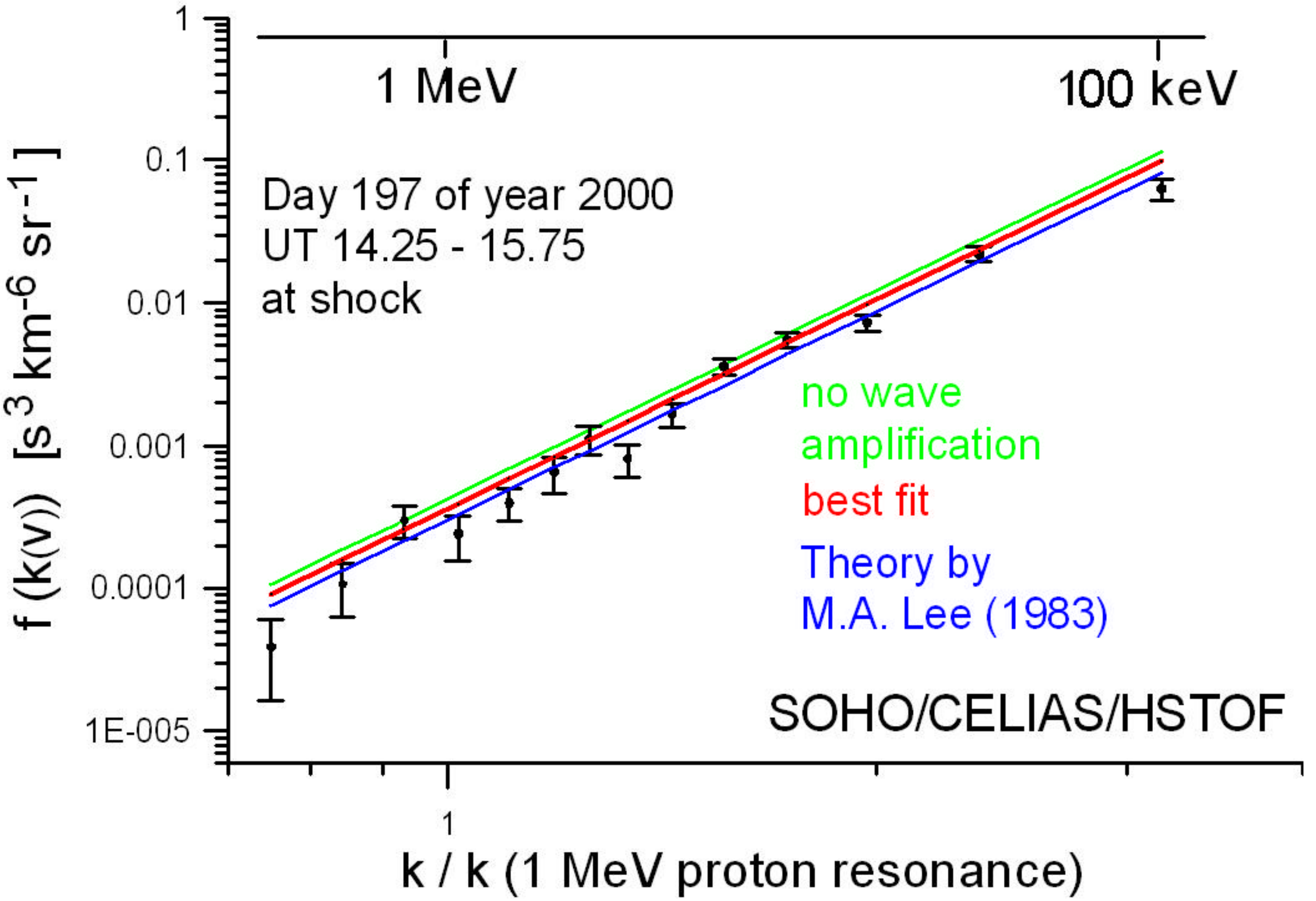
of the protons $f_{\rm p}(k, z)$

$$P(k, z) = \gamma_{\rm p} f_{\rm p}(k, z) + P(k, z = \infty)$$

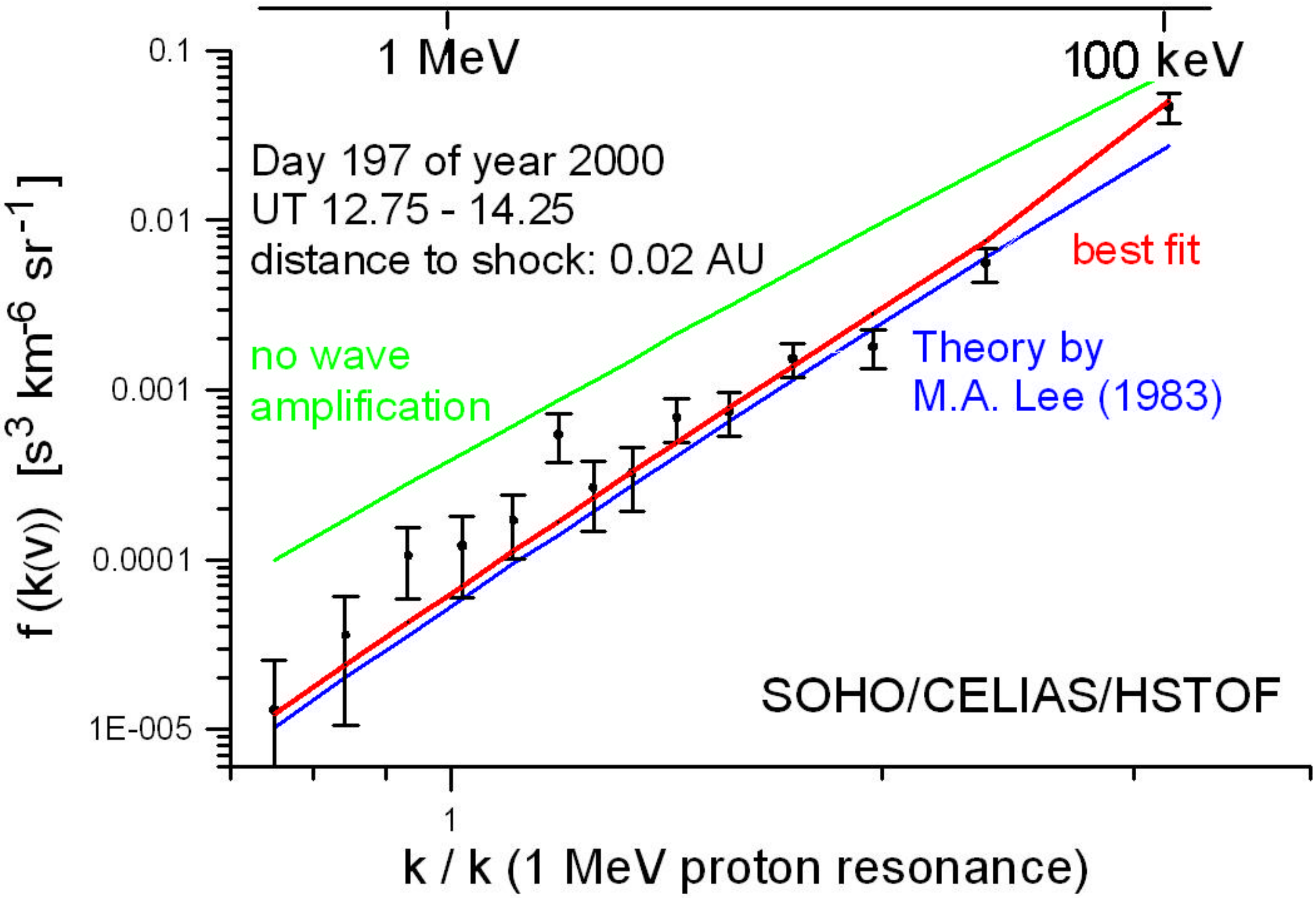
$$f_{\rm p}(k, z) \;=\; \frac{f_{\rm p}(k, 0)}{[1 + g(k)] \exp[h(k) z] - g(k)}$$

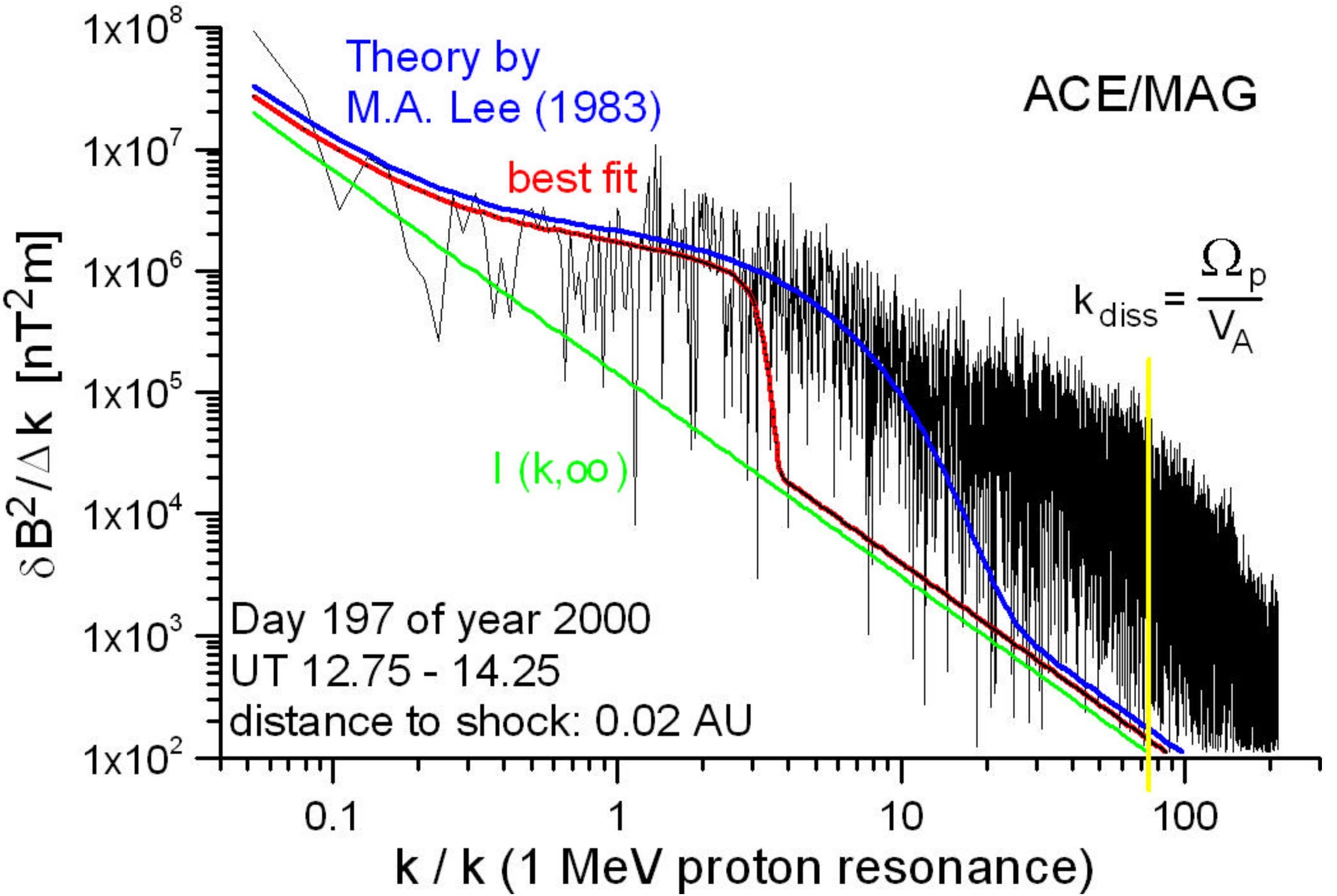


Day 197 of year 2000
UT 14.25 - 15.75
at shock
Theory by
M.A. Lee (1983)
I (k,∞)
ACE/MAG
δB²/Δk [nT²m]
k / k (1 MeV proton resonance)
1x10^11
1x10^10
1x10^9
1x10^8
1x10^7
1x10^6
1x10^5
1x10^4
1x10^3
1x10^2
0.1
1
10
100

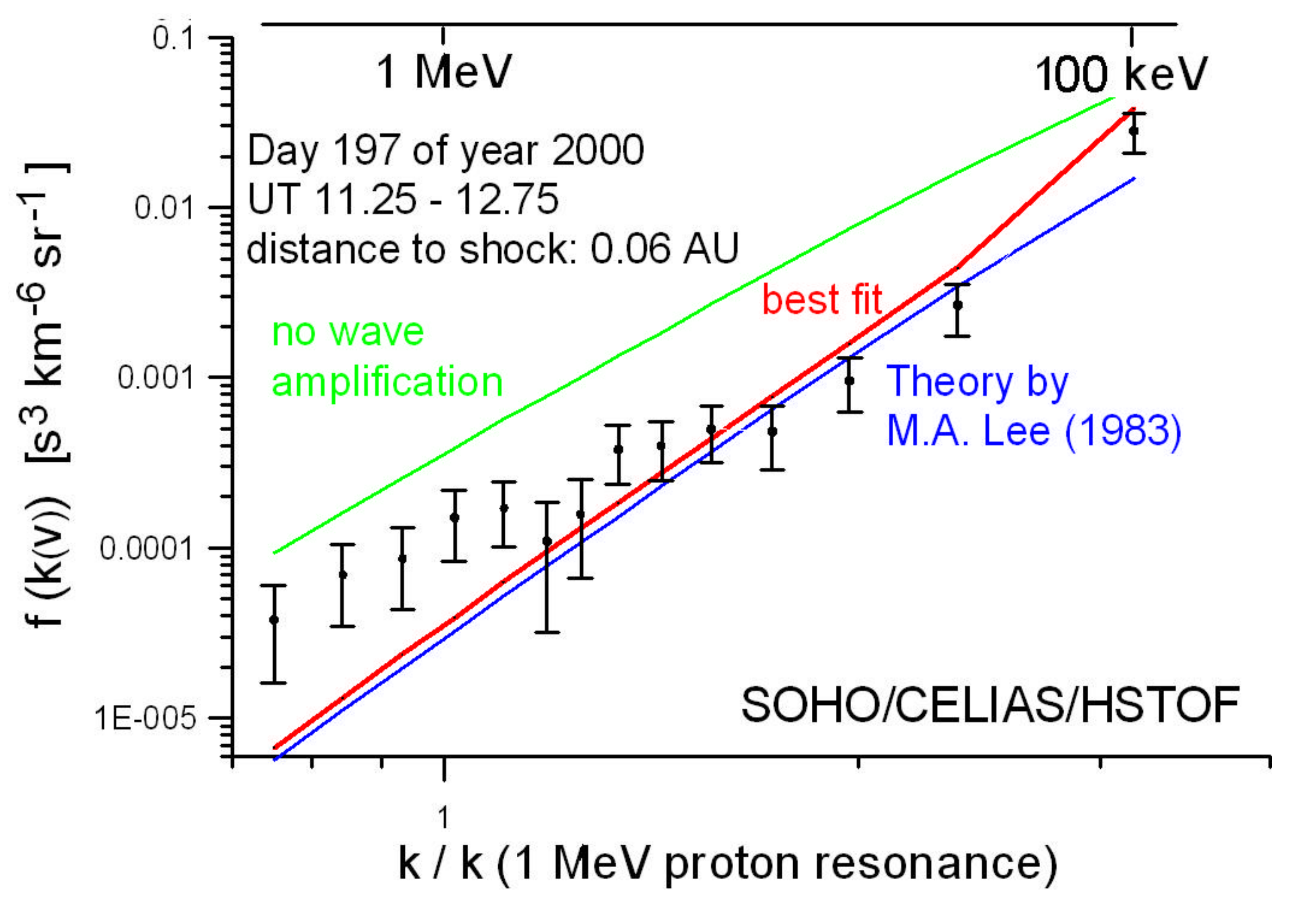


1 MeV
100 keV
f (k(v)) [s 3 km-6 sr-1]
1
0.1
0.01
0.001
0.0001
1E-005
Day 197 of year 2000
UT 14.25 - 15.75
at shock
no wave
amplification
best fit
Theory by
M.A. Lee (1983)
SOHO/CELIAS/HSTOF
k / k (1 MeV proton resonance)

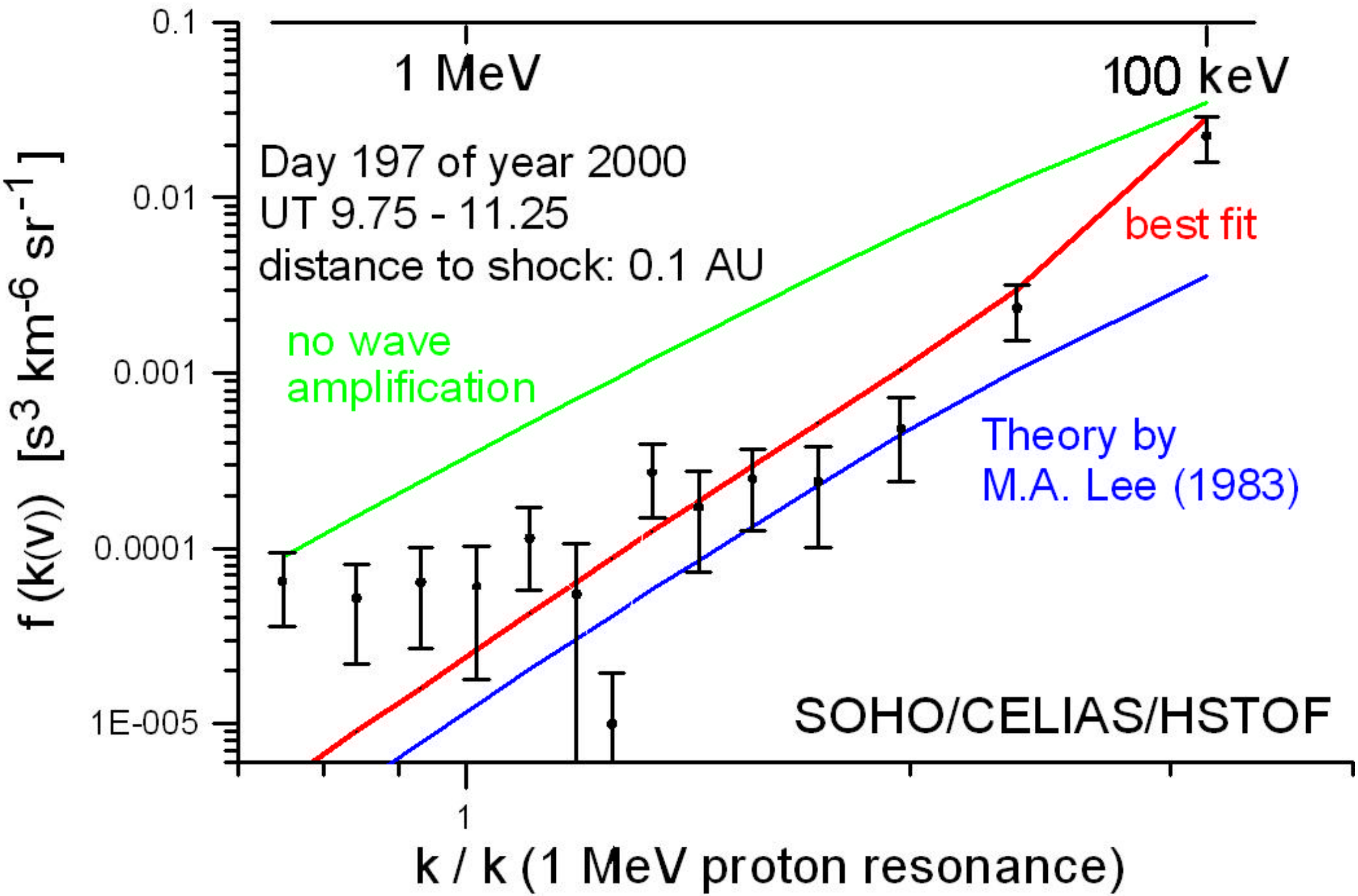

1 MeV
100 keV
0.1
0.01
0.001
0.0001
1E-005
f (k(v)) [s^3 km^-6 sr^-1]
Day 197 of year 2000
UT 12.75 - 14.25
distance to shock: 0.02 AU
no wave
amplification
best fit
Theory by
M.A. Lee (1983)
SOHO/CELIAS/HSTOF
1
k / k (1 MeV proton resonance)



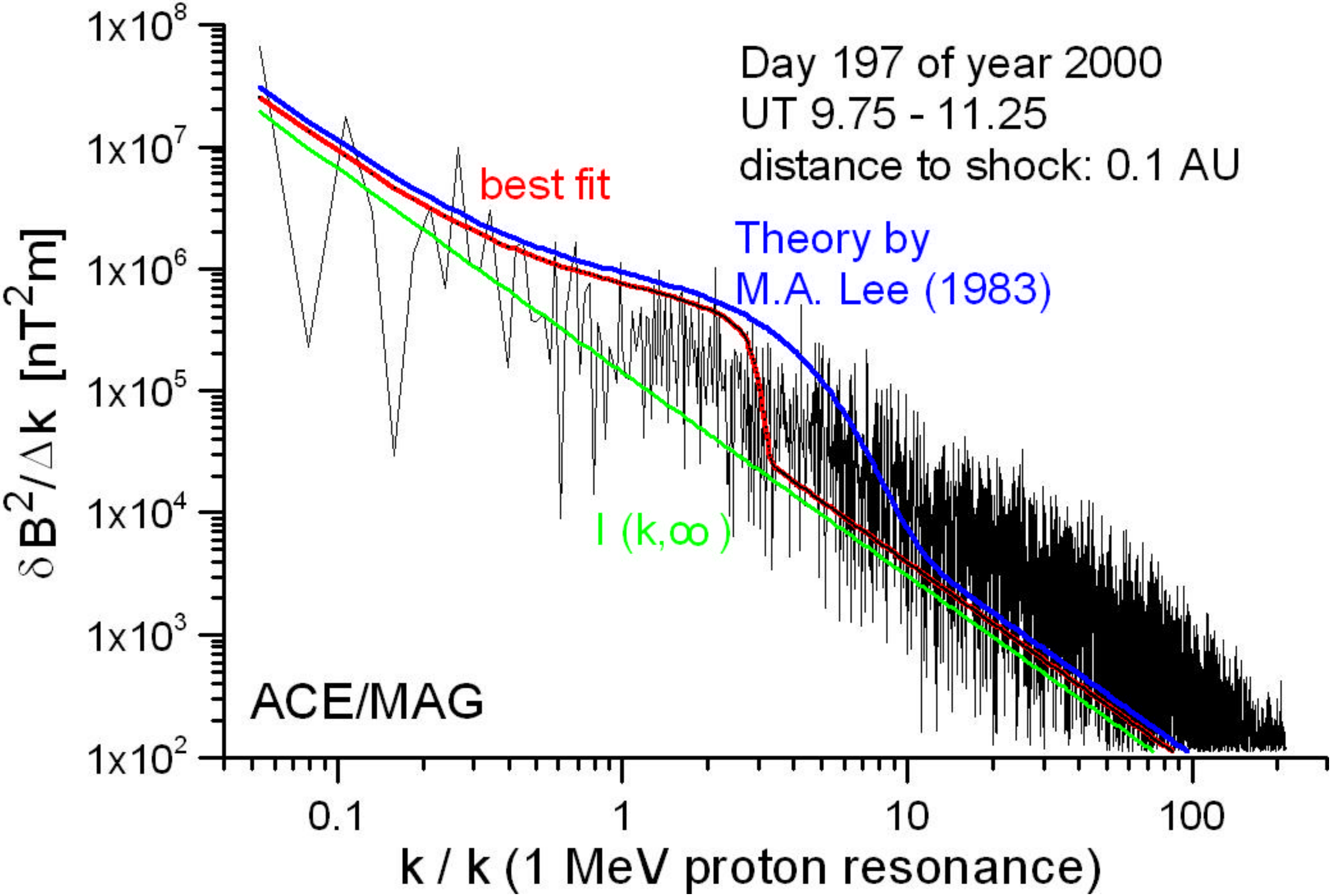
Theory by
M.A. Lee (1983)
ACE/MAG
best fit
$k_{diss} = \frac{\Omega_p}{V_A}$
I (k,oo)
Day 197 of year 2000
UT 12.75 - 14.25
distance to shock: 0.02 AU
$\delta B^2/\Delta k$ [nT^{2}m]
k / k (1 MeV proton resonance)
1x10^8
1x10^7
1x10^6
1x10^5
1x10^4
1x10^3
1x10^2
0.1
1
10
100



1 MeV
100 keV
Day 197 of year 2000
UT 11.25 - 12.75
distance to shock: 0.06 AU
no wave
amplification
best fit
Theory by
M.A. Lee (1983)
SOHO/CELIAS/HSTOF
0.1
0.01
0.001
0.0001
1E-005
1
f (k(v)) [s^3 km^-6 sr^-1]
k / k (1 MeV proton resonance)



0.1
0.01
0.001
0.0001
1E-005
1 MeV
100 keV
Day 197 of year 2000
UT 9.75 - 11.25
distance to shock: 0.1 AU
no wave
amplification
best fit
Theory by
M.A. Lee (1983)
SOHO/CELIAS/HSTOF
1
f (k(v)) [s3 km-6 sr-1]
k / k (1 MeV proton resonance)



Day 197 of year 2000
UT 9.75 - 11.25
distance to shock: 0.1 AU
best fit
Theory by
M.A. Lee (1983)
I (k,∞)
ACE/MAG
δB²/Δk [nT²m]
1x10⁸
1x10⁷
1x10⁶
1x10⁵
1x10⁴
1x10³
1x10²
0.1
1
10
100
k / k (1 MeV proton resonance)

$$P(k,z) = \gamma_{\mathrm{p}} f_{\mathrm{p}}(k,z) + P(k, z=\infty)$$

$$f_{\mathrm{p}}(k,z) = \frac{f_{\mathrm{p}}(k,0)}{[1+g(k)]\exp[h(k)z] - g(k)}$$

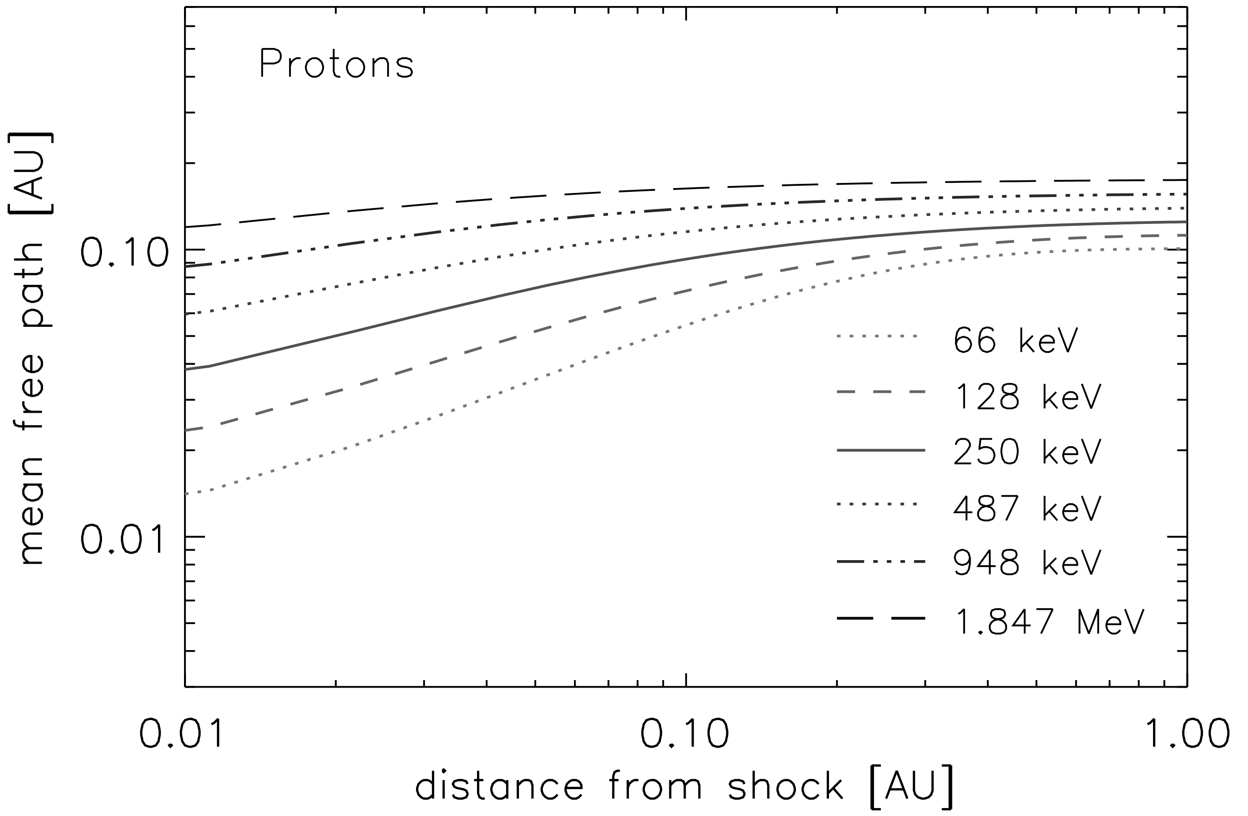
$$h(k) \approx 1.65\,(k/k_{1\mathrm{MeV}})^{4/3}\ \mathrm{AU}^{-1}$$

$$\gamma_{\mathrm{p}} \approx 5\times 10^{7}\,(k/k_{1\mathrm{MeV}})^{-6}\ \mathrm{km}^{6}\,\mathrm{s}^{-3}\,\mathrm{m}$$

$$P(k,z) = \frac{\delta\tilde{B}^2(k)}{B_0^2}; \qquad \gamma_{\mathrm{p}} \approx \frac{3\pi^2\Omega_{\mathrm{p}}^5}{[\beta(\beta-2)\,k^6 N_{\mathrm{p}} V V_{\mathrm{A}}]}$$

$$h(k) = \frac{V P(k,\infty)}{\kappa_{\mathrm{p}}(k)}; \qquad g(k) = \frac{\gamma_{\mathrm{p}}(k) f_p(k,0)}{P(k,\infty)}$$

$$\kappa_{\mathrm{p}}(k) = \Omega_{\mathrm{p}} k^{-3}/(8\pi)$$


Protons
mean free path [AU]
0.10
0.01
66 keV
128 keV
250 keV
487 keV
948 keV
1.847 MeV
0.01
0.10
1.00
distance from shock [AU]

Conclusions

- Mean free paths of protons below 2 MeV in solar wind plasma turbulence are smaller than predicted by quasi-linear theory.
- Asymmetries in distributions of protons at energies > 150 keV upstream of an interplanetary traveling shock drive hydromagnetic waves.
- These hydromagnetic waves reduce the scattering mean free path of the protons sufficiently to enable first-order Fermi acceleration.