Cosmic Ray Electron Transport and Radiation in the Inner Heliosphere and *RHESSI* Observation of the Quiet Sun

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With

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RHESSI 2021

Outline

I. Motivation

RHESSI Hard X-ray Observation of the Quiet Sun

II. Possible Emission Mechanism

Synchrotron Emission by Cosmic Ray Electrons

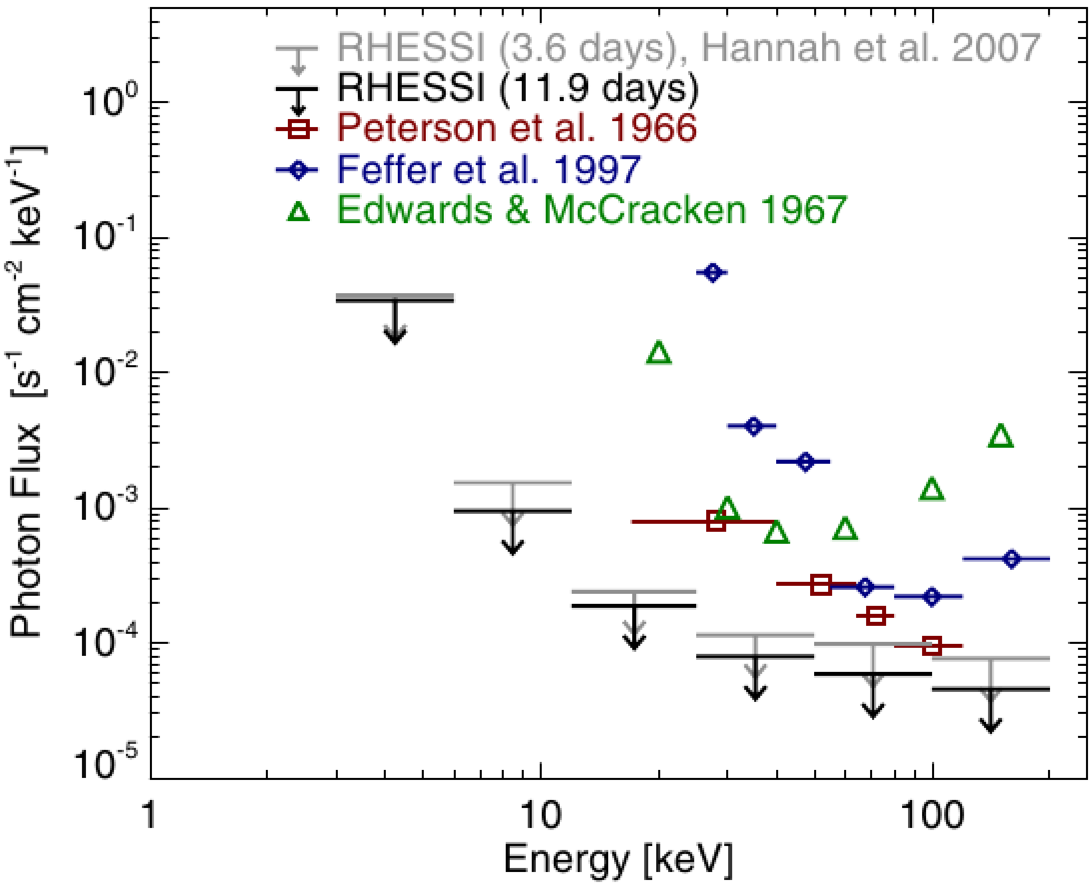
III. Transport of Cosmic Ray Electrons from 1 AU whwre they are Observed to the Sun

Effects of B Field Convergence, Scattering by Turbulence and Energy Loss

IV. Electron Spectral Evolution to the Sun and Disk Emission

I. Motivation

RHESSI and Other Hard X-ray Observation of the Quiet Sun



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II. Emission Mechanism

I. Thermal and Non-thermal *(thick-target Bremsstrahlung)*

Limits on Temperature and Emission Measure OR Spectral Index and Low Energy cut off

II. Axions

Limits on Axion-Photon Coupling Constant and B field

III. Synchrotron Emission by Cosmic-Ray Electrons

For production of *1-100 keV* photons need *100 to 1000 GeV* Electrons in *B=10 Gauss*

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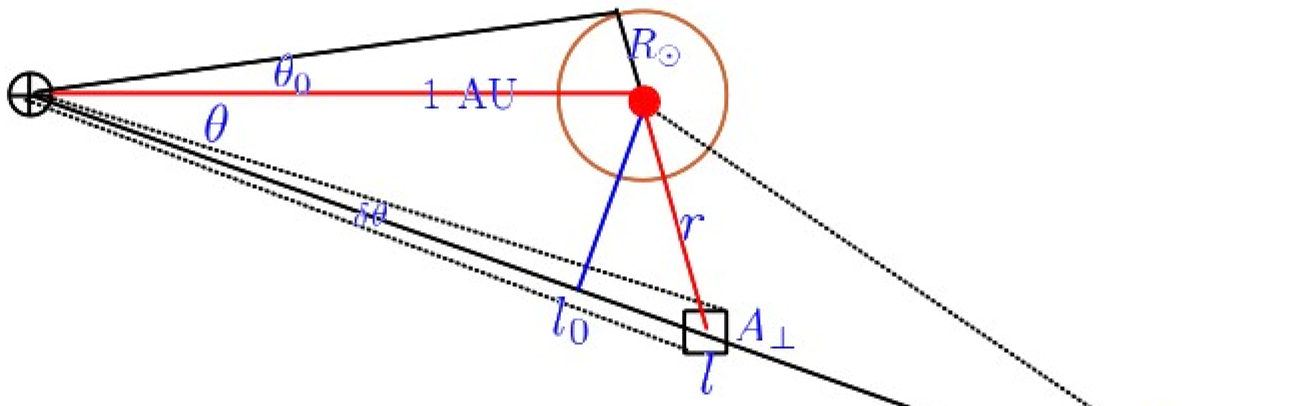
$$f(\nu,\gamma,r) = \frac{\sqrt{3}}{2\pi}\alpha_{fs} h\nu_B(r)(\nu/\nu_c)\int_{\nu/\nu_c}^{\infty} K_{5/3}(x')dx'; \quad \nu_c = \frac{3\gamma^2 eB(r)}{4\pi m_e c}$$

$$\eta(\nu,r) = \int_{\gamma_1}^{\infty} N(\gamma,r) f(\nu,\gamma,r) d\gamma$$

Basic Model

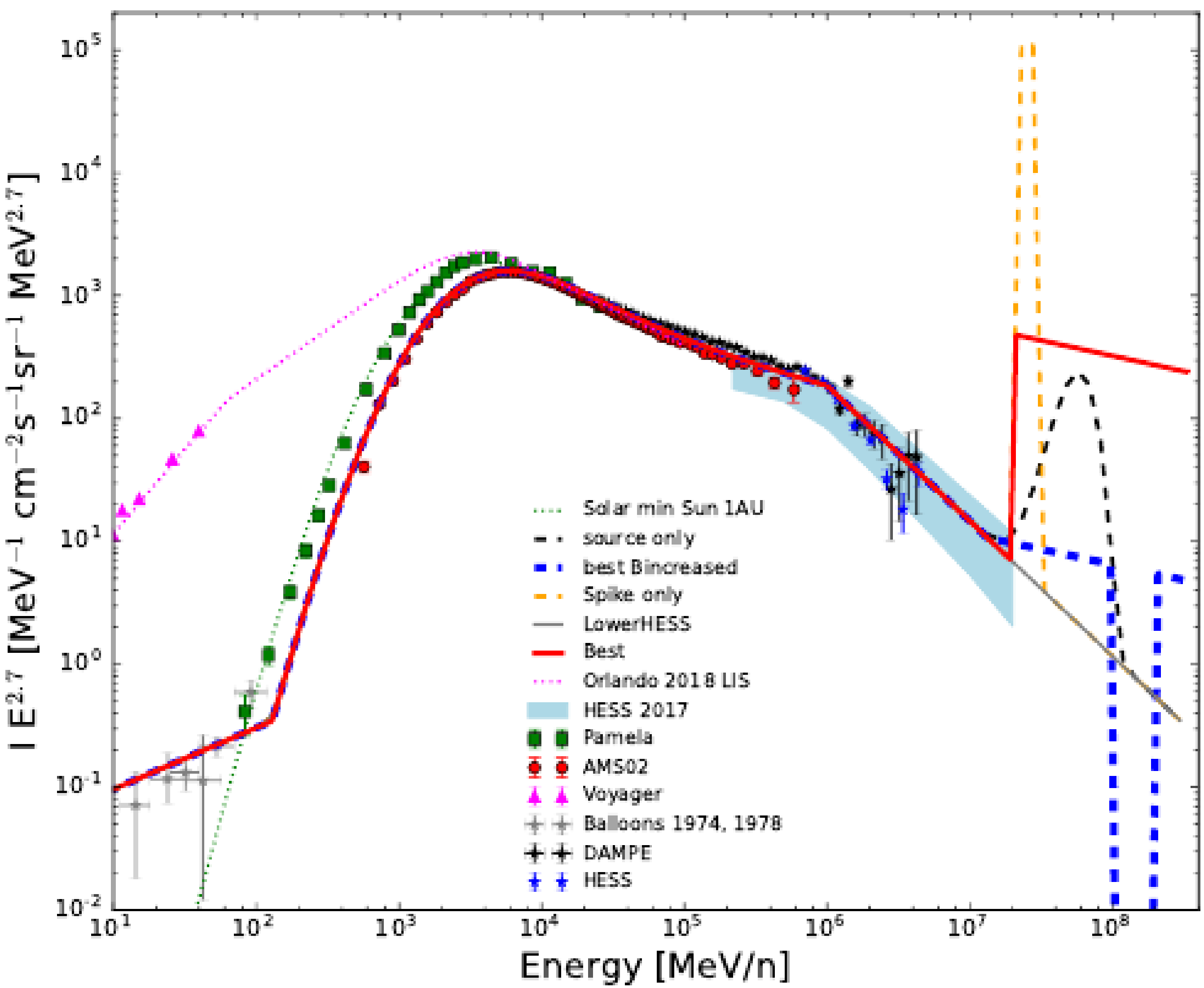
Geometry of Flux Calculation



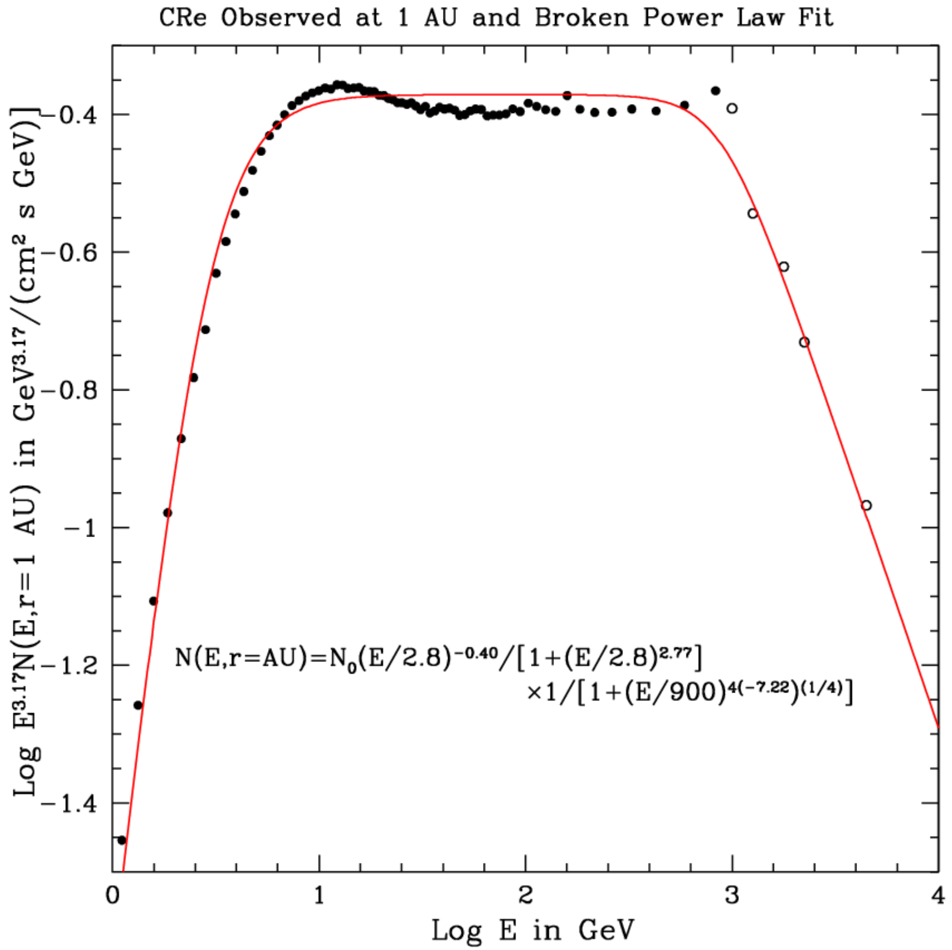
$$F(\nu,\theta) = \int_0^\infty \frac{\eta(\nu,r)dV/dl}{4\pi l^2} dl = \frac{d\Omega}{4\pi} \int_0^\infty \eta(\nu,r)dl$$

$$F(\nu,\theta) = \frac{\Omega}{2\pi} \int_{x_\theta}^{1/\sin\theta_0} \eta(\nu, r = xR_\odot) \frac{x\,dx}{\sqrt{x^2 - x_\theta^2}}; \quad x_\theta = \frac{\sin\theta}{\sin\theta_0}, \quad \sin\theta_0 = \frac{R_\odot}{AU}$$

Cosmic Ray Electron Spectrum at 1 AU



Cosmic Ray Electron Spectrum



$$N(E, r = AU) = N_0 \frac{(E/E_1)^{-0.4}}{1 + (E/E_1)^{2.77}} \frac{1}{[1 + (E/E_2)^{4(-7.22)}]^{1/4}}$$

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III. Cosmic Ray Transport

Fokker-Planck Kinetic Equation

$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial s} + \frac{v\partial \ln B}{2\partial s}\frac{\partial}{\partial \mu}\left[(1-\mu^2)f\right] = \frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu}\right] + \frac{\partial(\dot{E}f)}{\partial E} + \dot{Q}(t,\mu,E)$$

$$H_B = (d\ln B/dr)^{-1}, \quad \eta = 2.4r/H_B \sim 2.4\delta < 5$$

$$D_{\mu\mu}/v \sim 1/\lambda_{mfp} = 1/(v\tau_{\rm sc})$$

$$\frac{\dot{E}}{v} = \frac{d\gamma}{dr} = 1.2\frac{2}{3}r_0^2(\gamma^2-1)(1-\mu^2)\frac{B_{\rm eff}^2}{(m_e c^2)}$$

$$B_{\rm eff}^2 = B^2 + B_{\rm op}^2; \quad B = B_0(r/R_\odot)^{-\delta}, \quad B_{\rm op} = 7.4(r/R_\odot)^{-1}$$

$$\frac{d\mu}{dl} = \left(\frac{2r_0^2}{3m_e c^2}\right)\mu(1-\mu^2)B^2/\gamma$$

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III. Cosmic Ray Transport

An Approximate Treatment: spatially integrated

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right) - \frac{\partial}{\partial E}[(A - \dot{E}_L)N] - \frac{N}{T_{\rm esc}} + \dot{Q}$$

Strong diffusion $T_{\rm esc} \sim \tau_{\rm cross}^2/\tau_{\rm sc}$

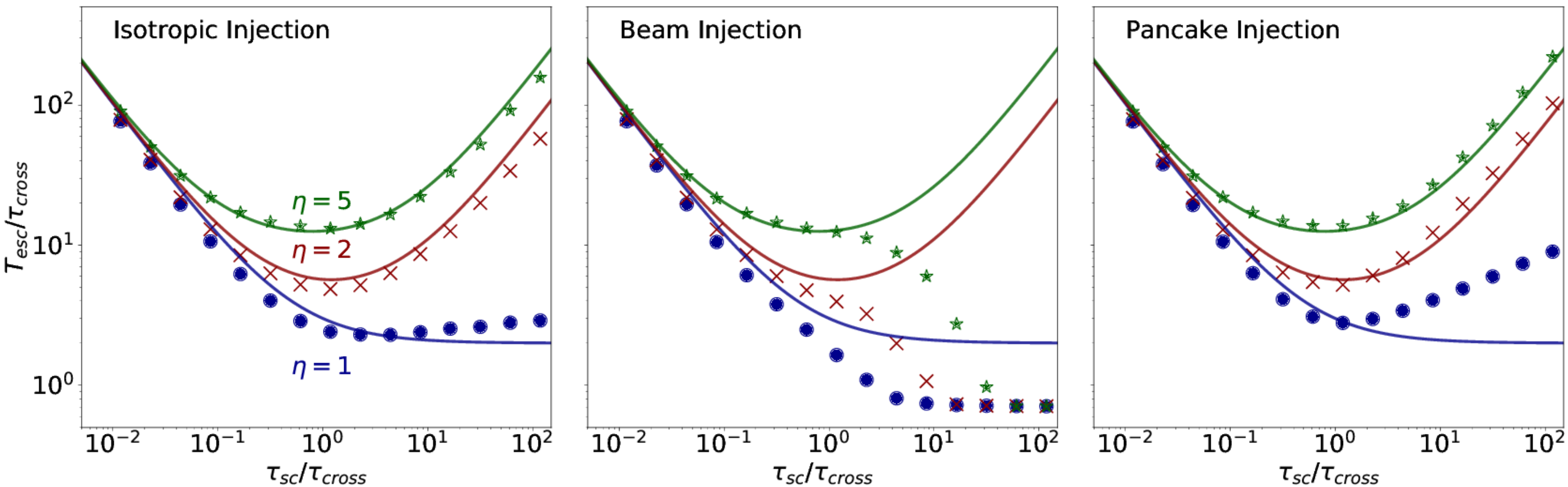
Weak diffusion $T_{\rm esc} \sim \tau_{\rm cross}$

Converging B-field $T_{\rm esc} \propto \tau_{\rm sc}$

Combined equation (For isotropic injection)

$$R = T_{\rm esc}/\tau_{cr} = \tau_{cr}/\tau_{\rm sc} + 2\eta + \ln\eta(\tau_{\rm sc}/\tau_{cr})$$

Simulation Results (F. Effenberger & VP, 2018, ApJ, 868, L28)



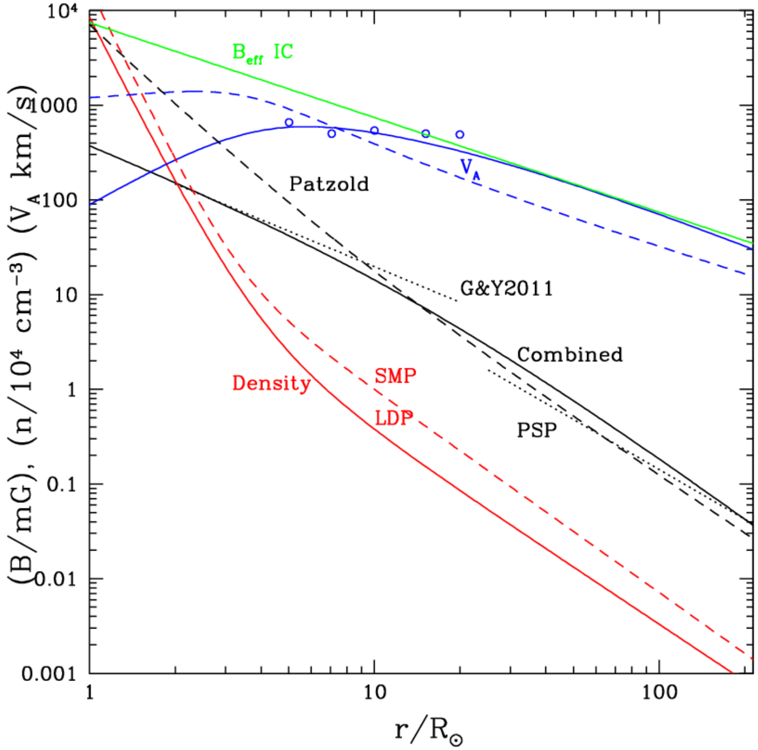
III. Cosmic Ray Transport

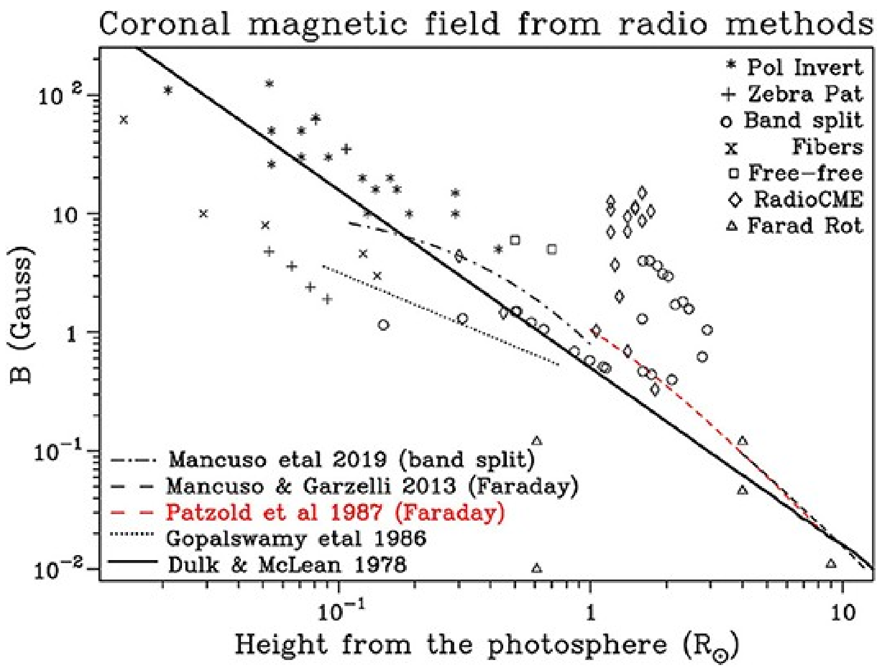
Energy Loss Rate

Synchrotron and Inverse Compton Losses

$$\frac{d\gamma}{dr} = 1.2\frac{2}{3}r_0^2(\gamma^2-1)(1-\mu^2)\frac{B_{\rm eff}^2}{(m_e c^2)}$$

Magnetic Field Structure





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III. Cosmic Ray Transport

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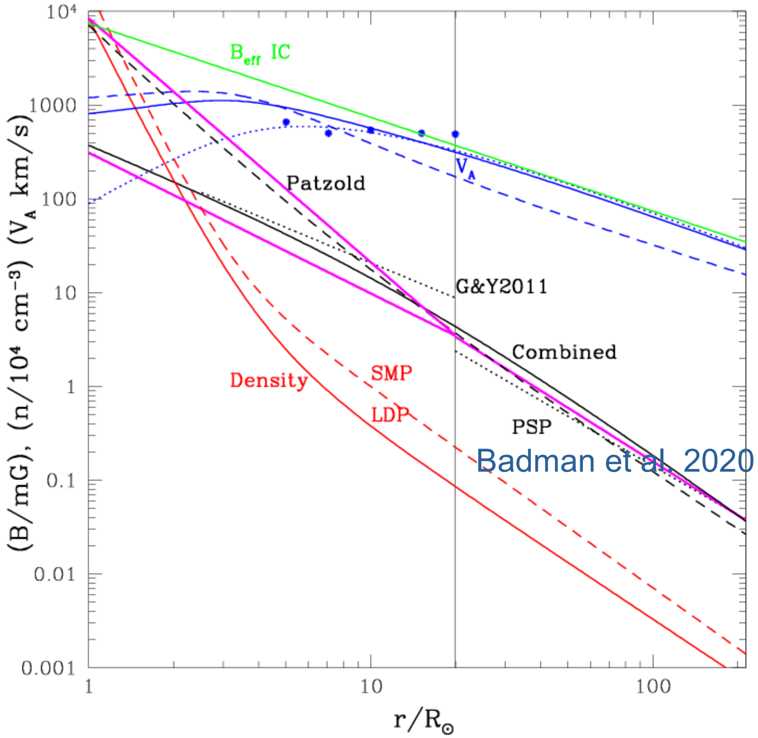

$$B(r)/{\rm G} = \begin{cases} 1.0(r/R_\odot)^{-1.9} & 0.1 < r/{\rm AU} < 1 \\ 0.31(r/R_\odot)^{-1.5} & {\rm GY11} \\ 8.4(r/R_\odot)^{-2.6} & {\rm Potzold.} \end{cases}$$

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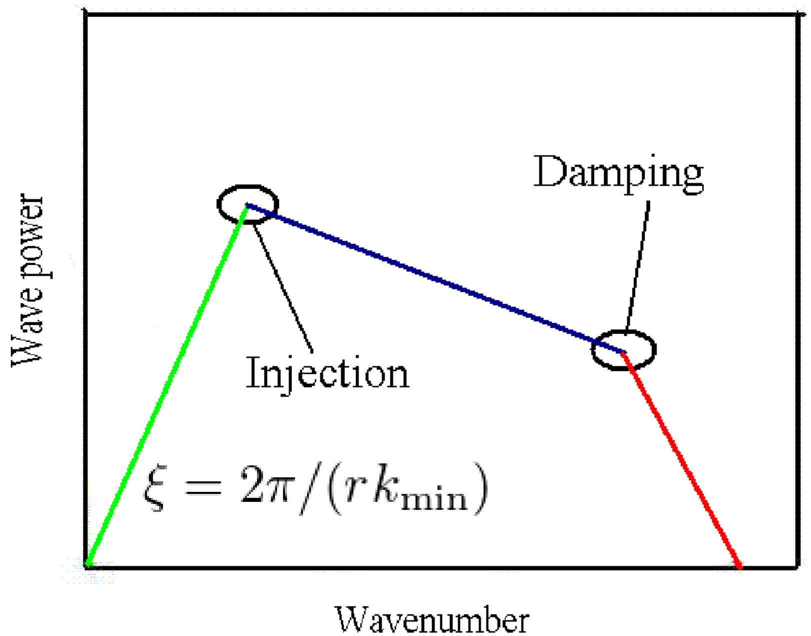
III. Cosmic Ray Transport
Scattering Time (or Mean Free Path)

Relativistic Electrons with Lorentz Factor > 2000

Scattered by Alfven Waves and Fast Mode Waves

Pryadko \& VP 1997



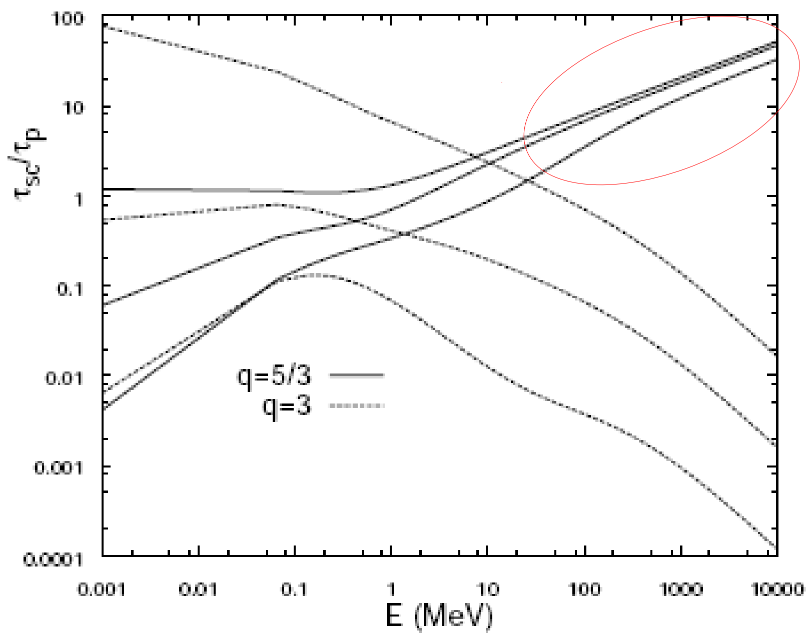


FIG. 12.—Same as Fig. 11, except for τ_{sc} from eq. (30) and for $\alpha = 10$, 1.0, and 0.1 from top to bottom.

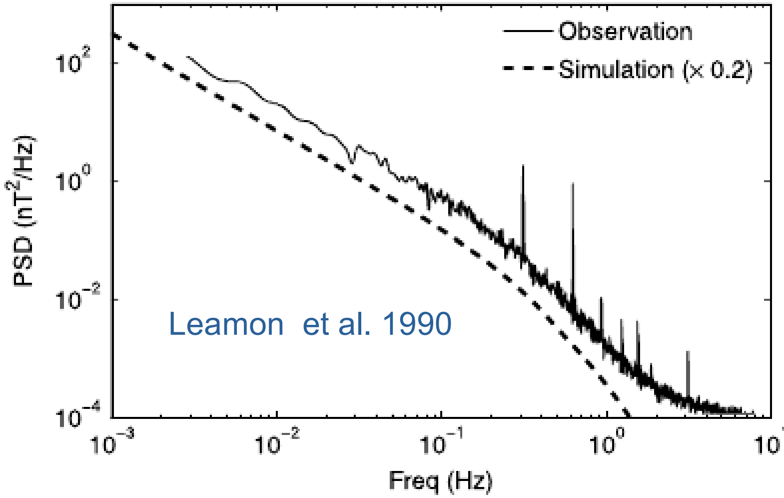
$$\tau_p^{-1} = \left(\frac{\pi}{2}\right)\Omega_e\left(\frac{u_{\rm turb}}{B^2/8\pi}\right)(q-1)\left(\frac{ck_{\min}}{\Omega_e}\right)^{q-1}$$

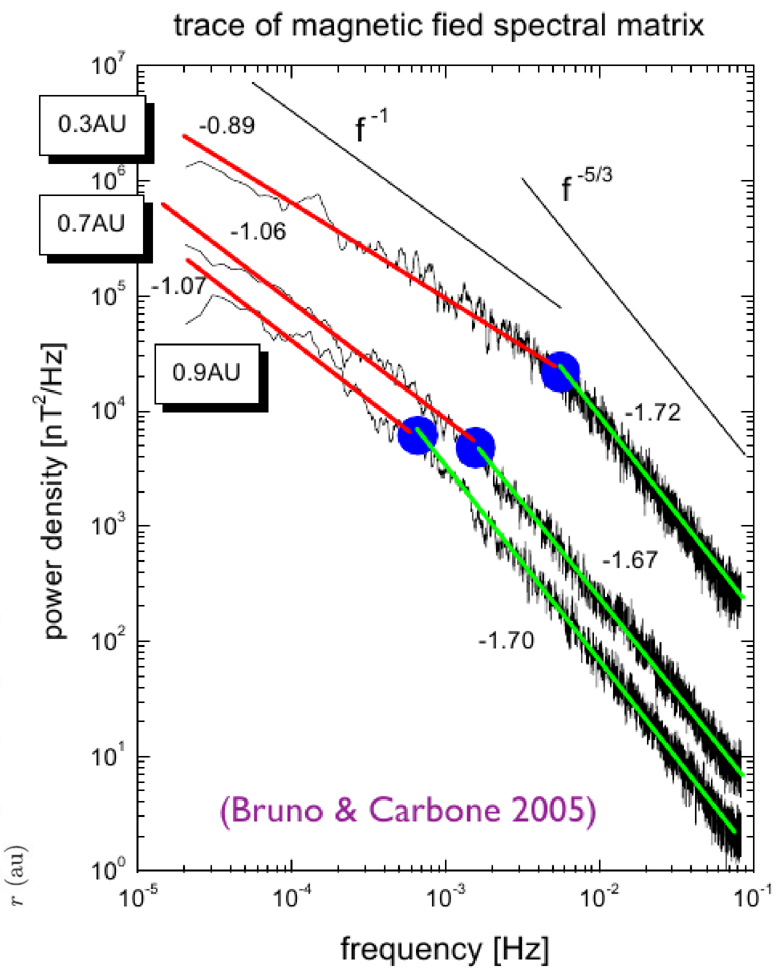
$$\alpha = \left(\frac{\omega_{pe}}{\Omega_e}\right) \propto \left(\frac{\sqrt{n}}{B}\right) \quad \text{and } u_{\rm turb} \sim 8\pi\delta B^2 \sim \rho v_{\rm turb}^2$$

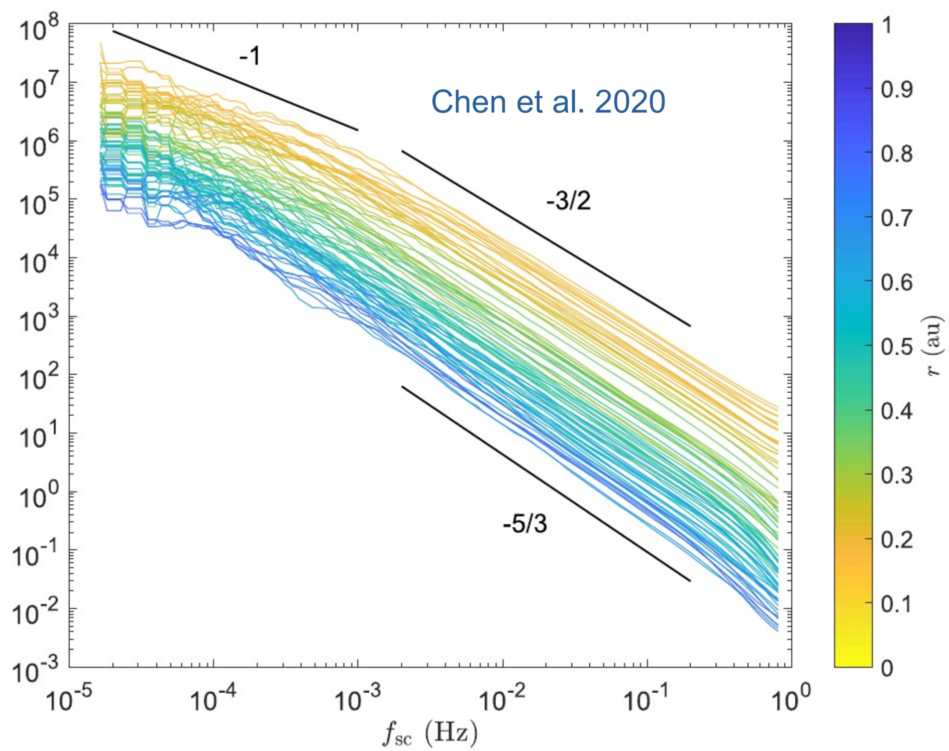
$$\frac{\tau_{sc}}{\tau_p} = \gamma^{(2-q)}\begin{cases} 2[(2-q)(4-q)]^{-1} & q < 2 \\ 3/4 - (1/2)\ln\beta_A & q = 2. \end{cases}$$

VP \&Liu 2004

Characteristics of Turbulence







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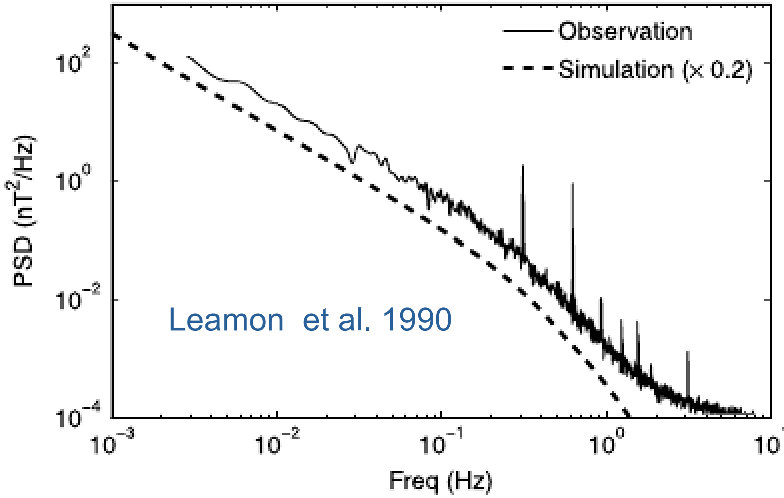
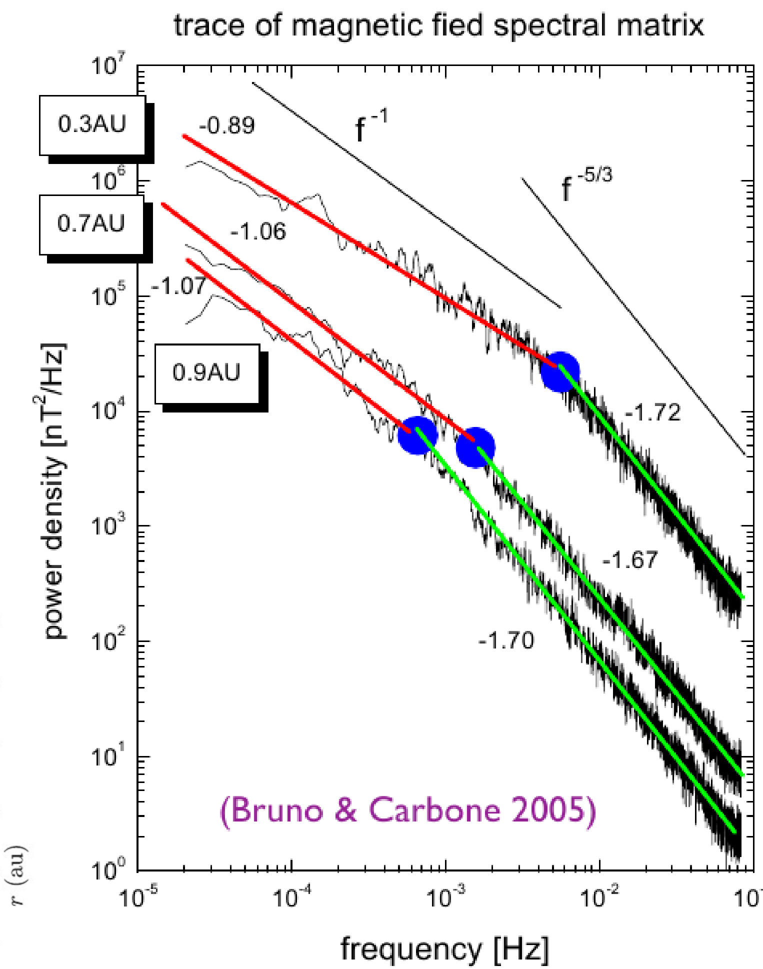
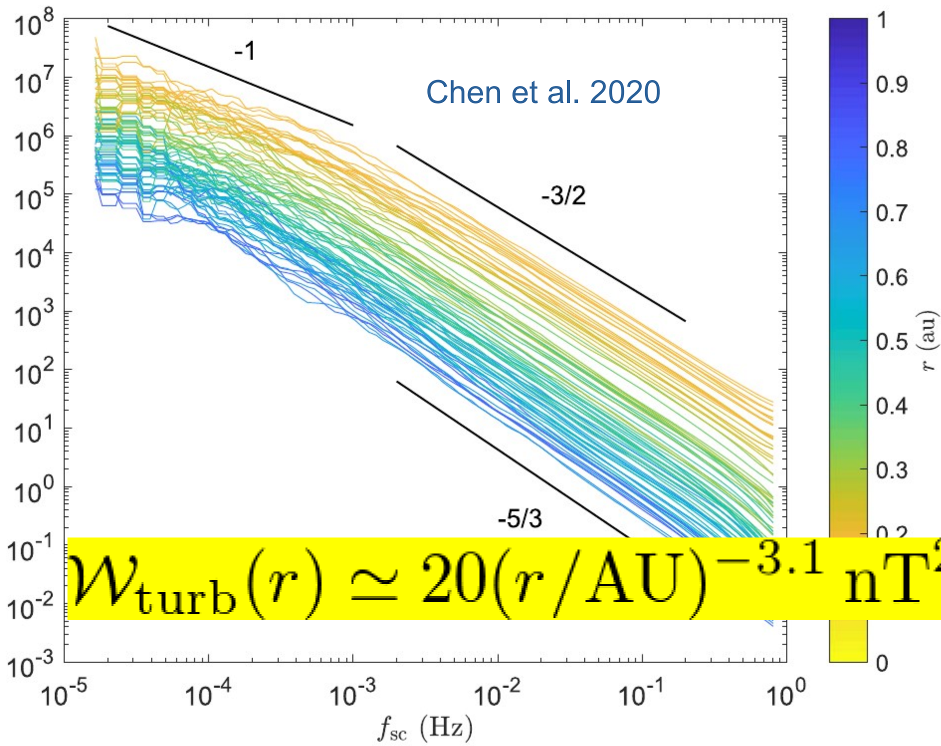
Characteristics of Turbulence







$$\mathcal{W}_{\rm turb}(r) \simeq 20(r/{\rm AU})^{-3.1}\ {\rm nT}^2 \quad 0.1 < (r/{\rm AU}) < 1$$

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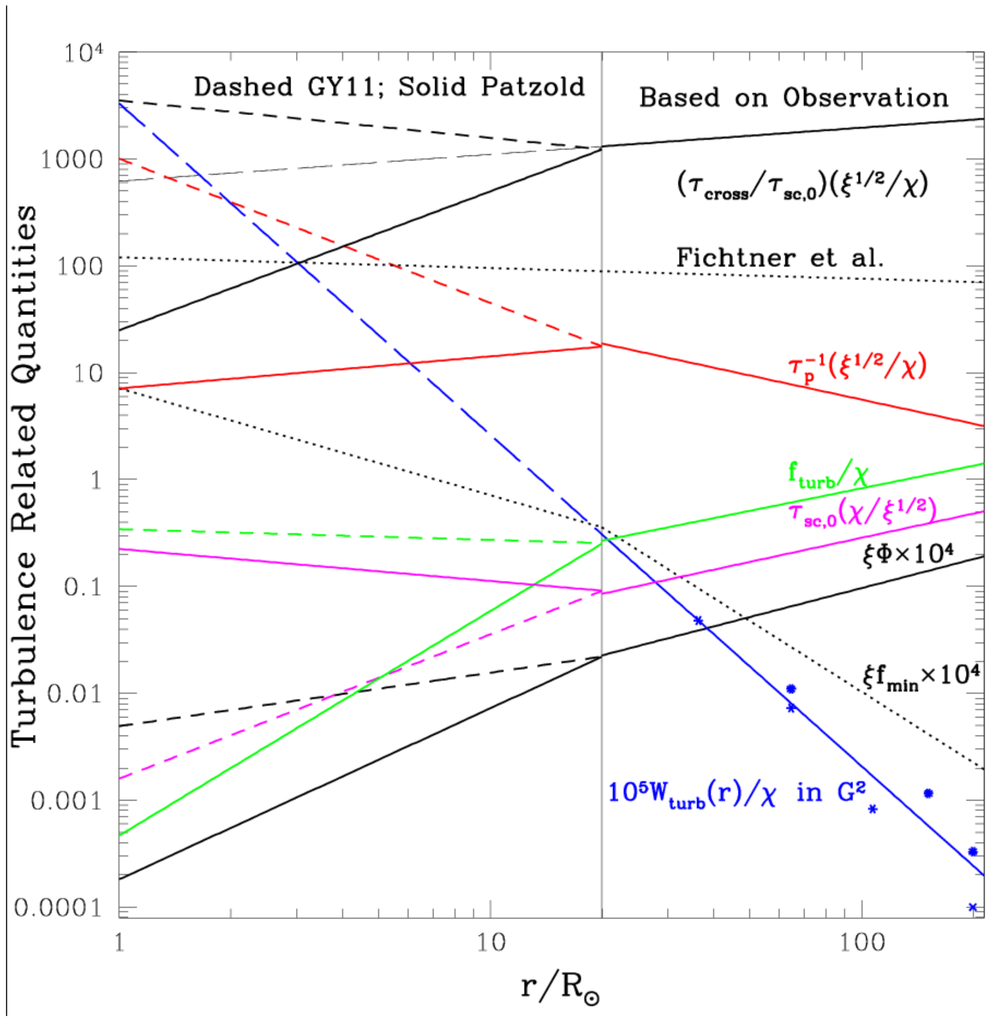
Turbulence and Scattering Time



$$\xi = 2\pi/(r k_{\min})$$

$$\chi = 1 + 0.1 Log\xi$$

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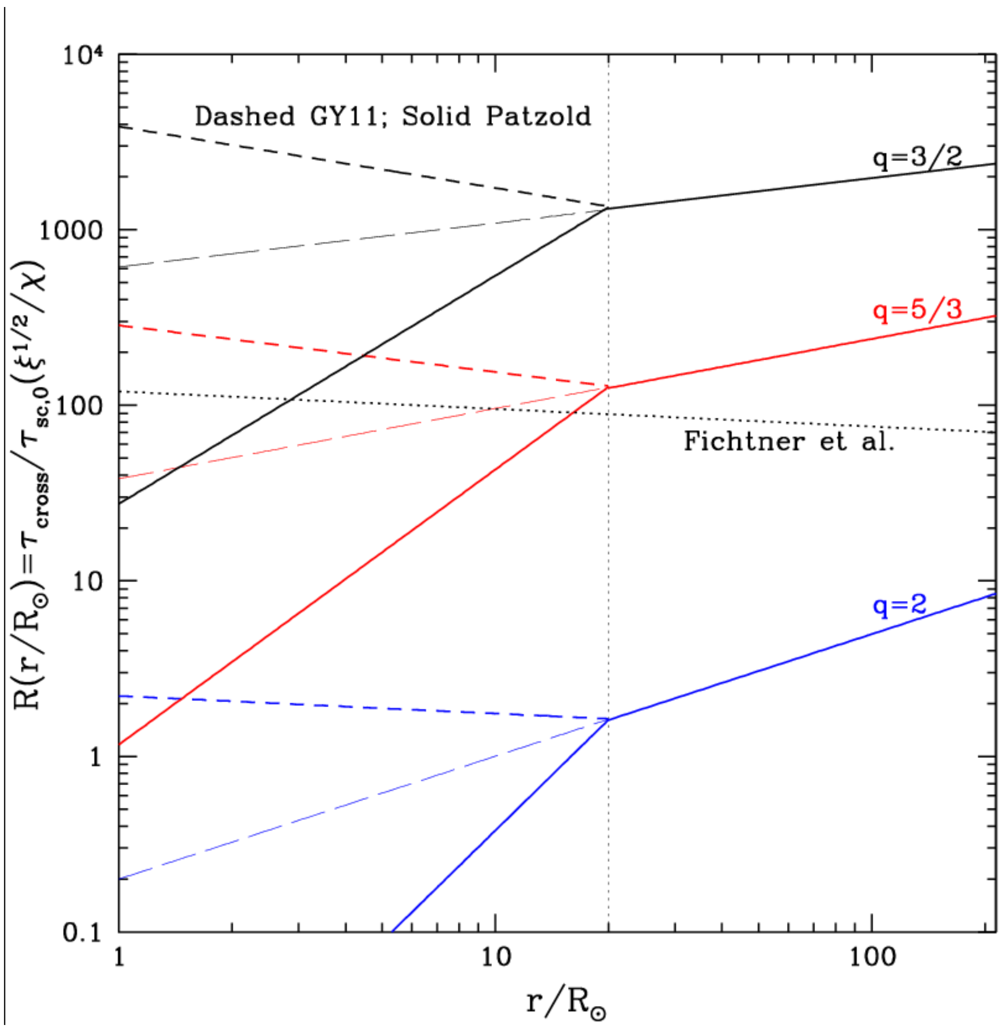
Crossing tp Scattering Time atios



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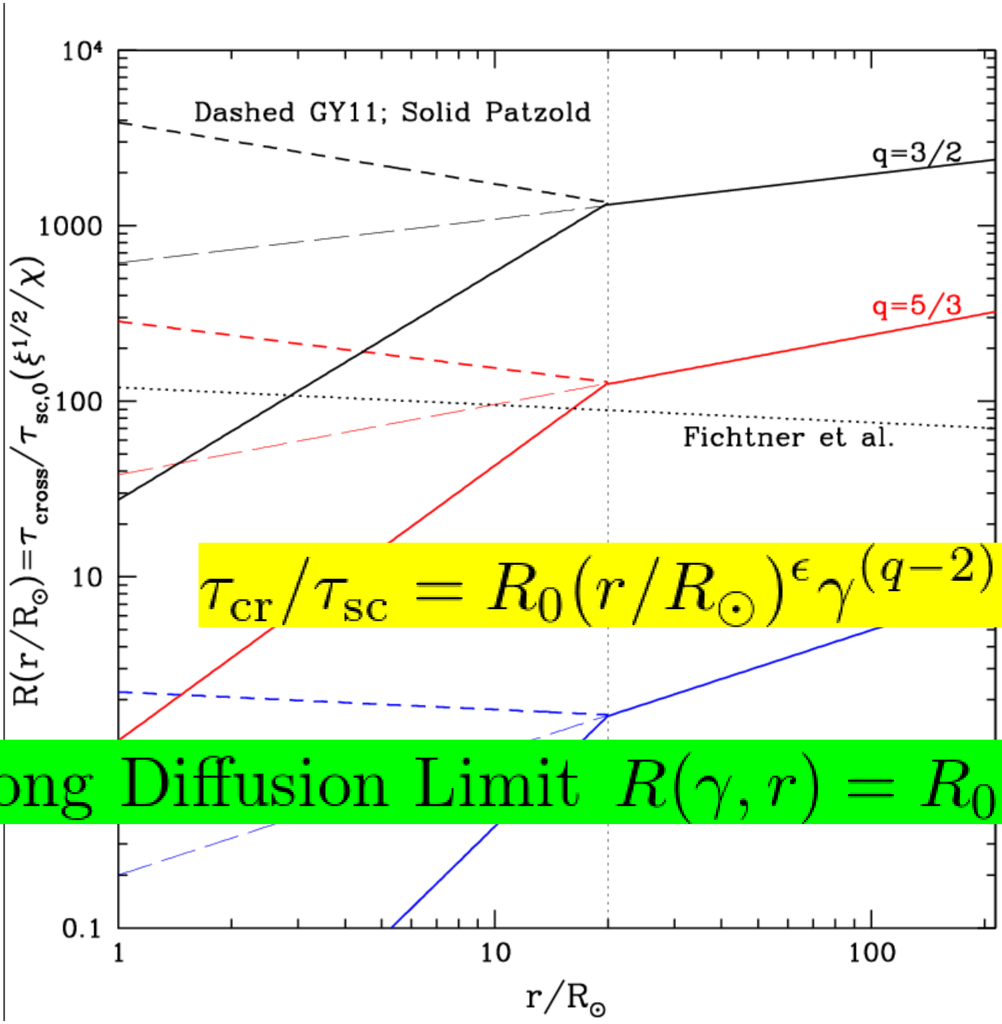
Cosmic Ray Transport



$$\xi = 2\pi/(r k_{\min})$$

$$\chi = 1 + 0.1 Log\xi$$

$$\tau_{cr}/\tau_{sc} = R_0(r/R_\odot)^\epsilon \gamma^{(q-2)} > 1$$

Strong Diffusion Limit $R(\gamma, r) = R_0(r/R_\odot)^\epsilon \gamma^{(q-2)}$

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Energy Loss and CRe Spectral Variation

$$d\gamma/dr|_{eff} = R(r,\gamma)d\gamma/dr$$

$$d\gamma/\gamma^q = Cg(r/R_\odot)d(r/R_\odot), \quad g(x) = x^\epsilon(x^{-2} + \zeta x^{-2\delta})$$

$$\gamma^{(1-q)} - \gamma_0^{(1-q)} = CG(r/R_\odot), \quad G(x) = \int_x^{x_{au}} g(x)dx$$

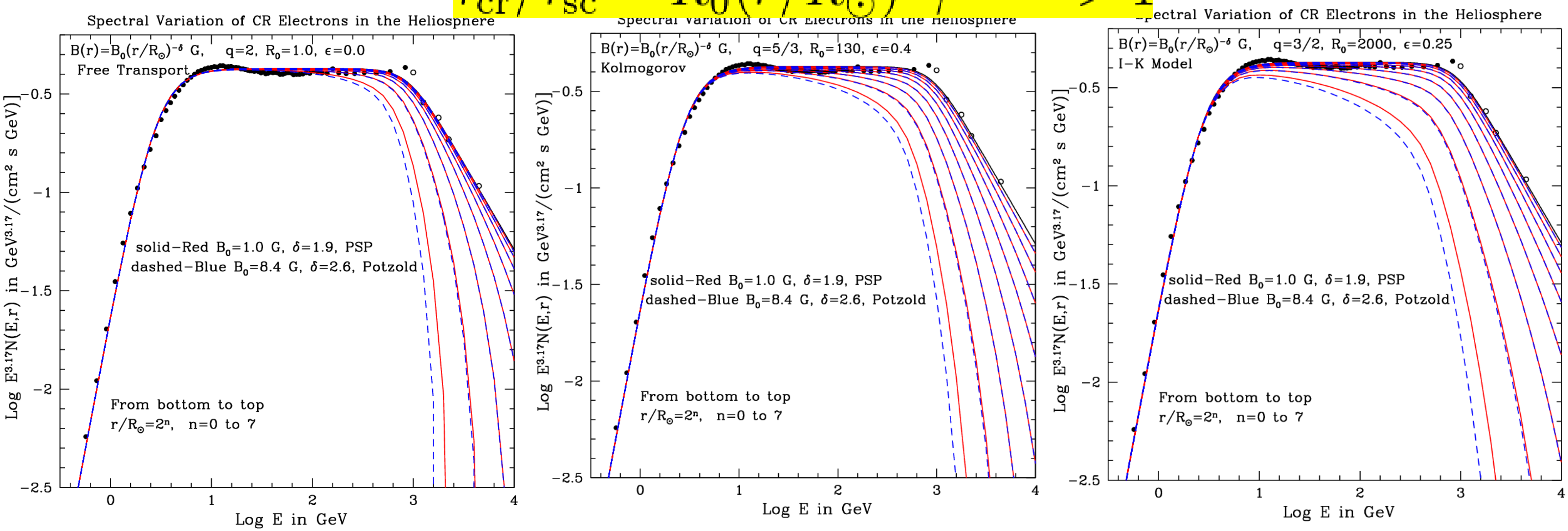
$$A(x,\gamma) = CG(r/R_\odot)\gamma^{(q-1)}$$

$$N(\gamma,r) = N_0\left(\frac{\gamma}{[1 - A(r/R_\odot)]^{1/(q-1)}}\right)[1 - A(r/R_\odot)]^{-q/(q-1)}$$

CRe Spectra Variation with Distance and Turbulence Spectral Index

$$N(\gamma, r) = N_0 \left(\frac{\gamma}{[1 - A(r/R_\odot)]^{1/(q-1)}} \right) [1 - A(r/R_\odot)]^{-q/(q-1)}$$

$$\tau_{\rm cr}/\tau_{\rm sc} = R_0 (r/R_\odot)^{\epsilon} \gamma^{(q-2)} > 1$$



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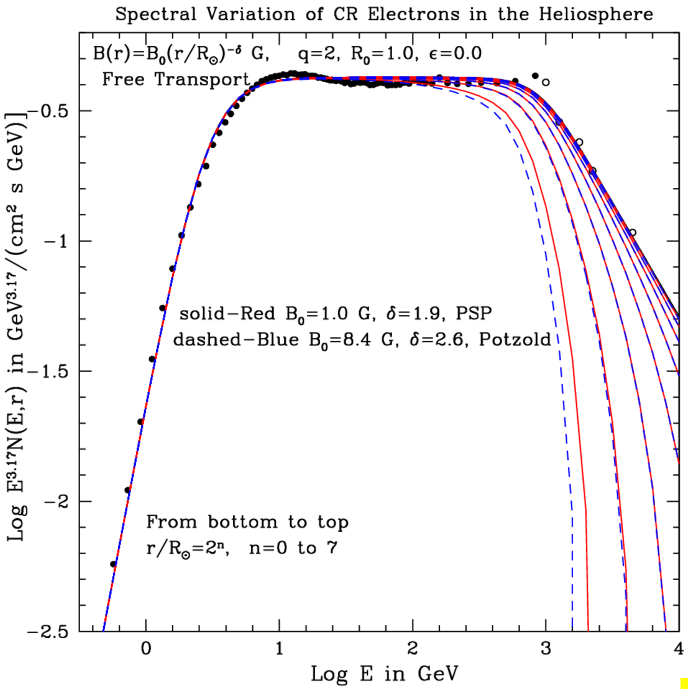
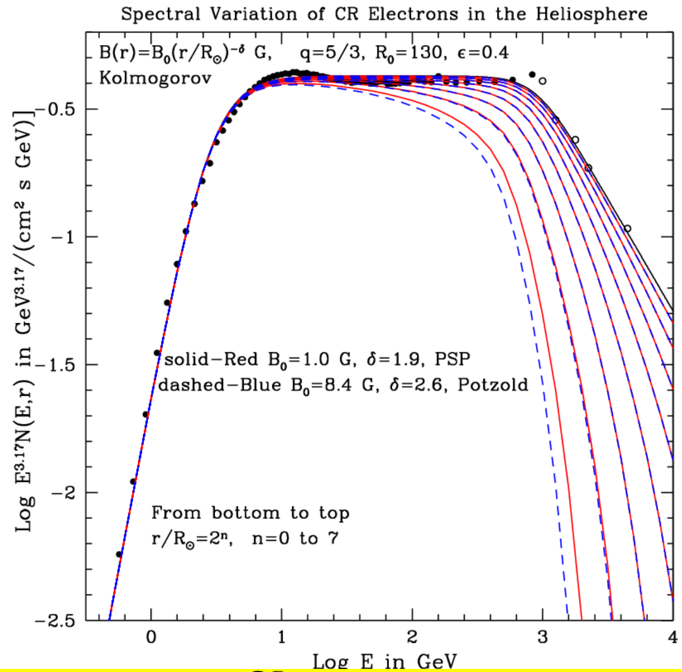
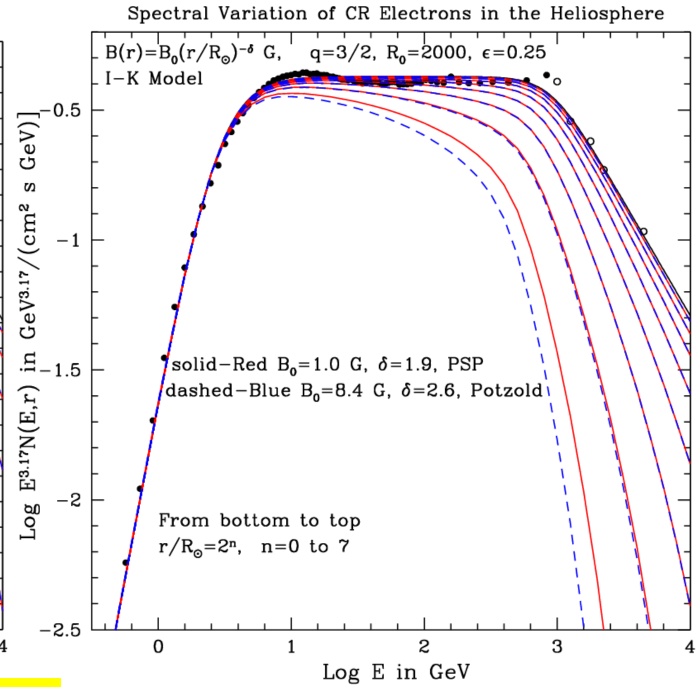
Synchrotron Flux at 1 AU at Different Angles

$$N(\gamma, r) = N_0 \left(\frac{\gamma}{[1 - A(r/R_\odot)]^{1/(q-1)}} \right) [1 - A(r/R_\odot)]^{-q/(q-1)}$$







$$\eta(\nu, r) = \int_{\gamma_1}^{\infty} N(\gamma, r) f(\nu, \gamma, r) d\gamma$$

$$F(\nu, \theta) = \frac{\Omega}{2\pi} \int_{x_\theta}^{1/\sin\theta_0} \eta(\nu, r = xR_\odot) \frac{x dx}{\sqrt{x^2 - x_\theta^2}}; \quad x_\theta = \frac{\sin\theta}{\sin\theta_0}, \quad \sin\theta_0 = \frac{R_\odot}{AU}$$

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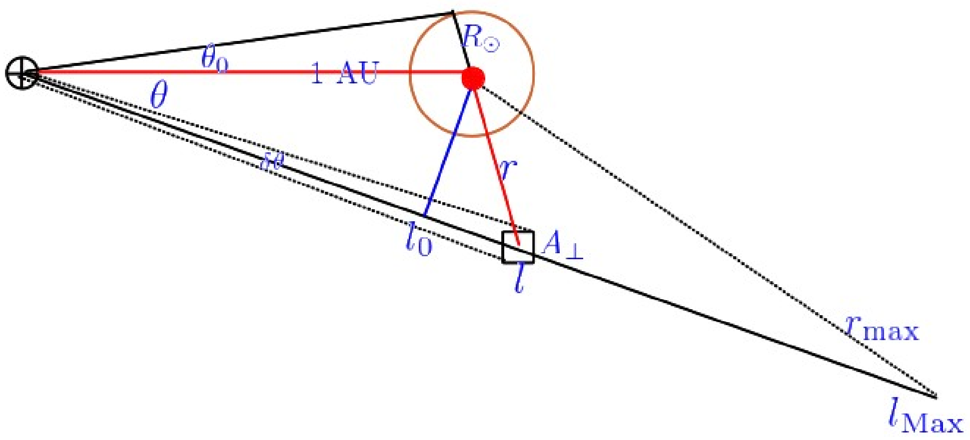
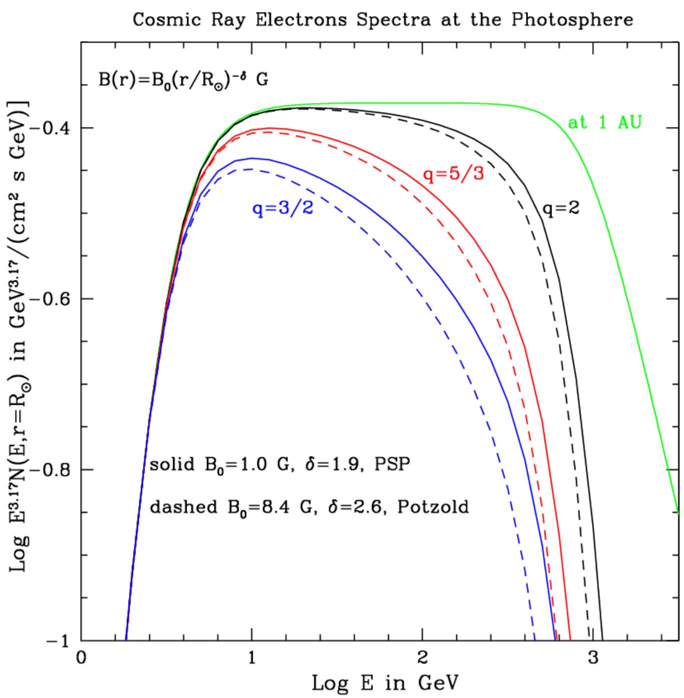
Synchrotron Flux at 1 AU From Solar Disk

$$F(\nu,\theta) = R_\odot \int_1^{1/\sin\theta_0} \eta(\nu, r = xR_\odot) x dx \int_0^{\theta_0} \frac{\sin\theta d\theta}{\sqrt{x^2 - (\sin\theta/\sin\theta_0)^2}}, \quad \sin\theta_0 = \frac{R_\odot}{AU}$$

Geometry of Flux Calculation





Integrate over θ $(0 \; to \; \theta_0 \ll 1)$; $\sin\theta = \theta$.

$$F_{\mathrm{disc}}(\nu) = R_\odot \sin\theta_0^2 \int_1^{a/R_\odot} \eta(\nu, x = r/R_\odot) x (x - \sqrt{x^2 - 1}) dx$$

Summary

1. Synchrotron emission by Cosmic Ray Electrons (CRes) in 10 Gauss B field can produce hard X-rays on the Sun
2. We Fit the CRe spectrum Observed at 1 AU by a double broken power law model with breaks at 10 and 1000 GeV.
3. We then calculate the spectral evolution to the Sun considering the effects of B field convergence, scattering by turbulence and energy losses.
4. This requires the characteristics of the turbulence and structure of the B field.
5. We use recent results from PSP and their extrapolation to the Sun and obtain the spectral evolution for several models.
6. These can be used to more accurate expected hard X-ray spectra which when compared with observations can constrain the model parameters.
7. Preliminary results are promising.