3He and heavy ion enrichment in solar energetic particles as evidence for cyclotron resonances with linear waves

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Abstract

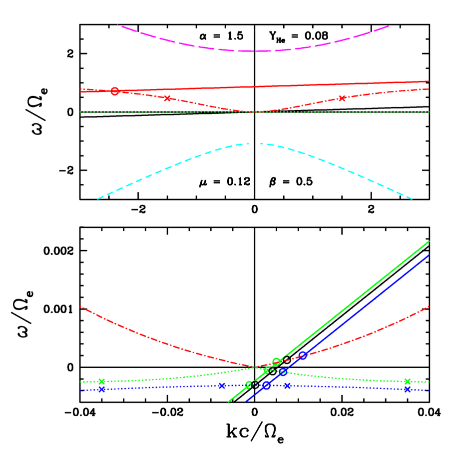
In this talk, I will draw distinction between linear plasma waves and strong turbulent fluctuations and argue general characteristics of 3He rich solar energetic particle events favor the scenario that 3He ions are mostly energized via cyclotron resonance with proton cyclotron waves. These waves can be produced via magnetic reconnection at the ion diffusion scale and/or via cascade of turbulence energy from low to high frequencies. Both PIC and hybrid simulations can be used to verify these scenarios.

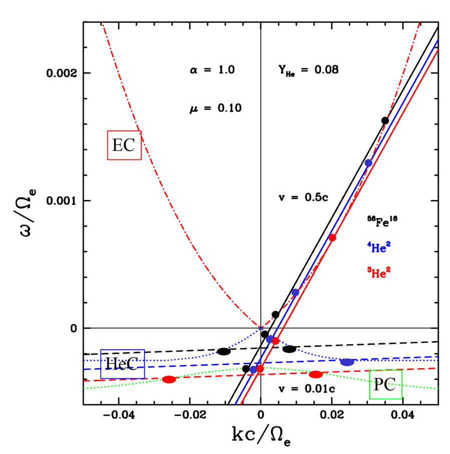
Linear Waves and Others

Dispersion Relation of Parallel Waves:

$$(ck)^2 = \omega^2\left[1-\sum_i \frac{\omega_{pi}^2}{\omega(\omega-q_i/|q_i|\Omega_i)}\right].$$

Resonance Condition: $\omega - k_\parallel \beta\mu = \frac{n\omega_i}{\gamma}$,





$\alpha = \frac{\omega_{pe}}{\Omega_e} = 1.0\left(\frac{n}{10^9\mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{B_0}{100\mathrm{G}}\right)^{-1}$

Y_{He}: *Helium abundance*

Linear waves have well-defined dispersion relations with the wave period much shorter than their decay time so that charged particles may exchange energy with them efficiently via resonances.

n=0 for transit-time damping (TTD) is for all particles moving with the waves and it is not selective in the sense that gyro-frequency of the particle is irrelevant. It leads to energization primarily for motion along the magnetic field.

For cyclotron resonances (CR) [1], particles with different gyro frequencies interact with different waves. Selective acceleration can be achieved since the waves are determined by properties of the background plasma.

Besides energy exchange with linear waves, particles may also change energy due to interactions with other electric field fluctuations, which is likely chaotic, leading to bulk energization of the background plasma.

Stochastic Particle Acceleration

For most cases of astrophysical particle acceleration, only spatially integrated and/or time averaged particle distributions are available. One may solve the Fokker-Planck equation for energy distribution of energized particles. Usually four processes need to be considered: energy diffusion and convection due to interactions with turbulent electromagnetic fields; energy loss due to Coulomb collisions and radiative processes; escape from the acceleration site and injection into the acceleration processes. First order Fermi acceleration can also be incorporated by introducing an extra convection term. In the high-energy regime, the injection can be ignored. The other three processes can be characterized via three timescales: acceleration, energy loss, and escape [1].

Fokker-Planck Equation

$$D_{ab} = \frac{(\mu^{-2}-1)}{\tau_{pi}\gamma^2}\sum_{j=1}^N \chi(k_j)\begin{cases}\mu\mu(1-x_j)^2 & \text{for } ab=\mu\mu,\\ \mu p x_j(1-x_j) & \text{for } ab=\mu p,\\ p^2x_j^2 & \text{for } ab=pp,\end{cases}$$

$$\chi(k_j) = \frac{|k_j|^{-q}}{|\beta\mu-\beta_g(k_j)|},\quad x_j=\mu\omega_j/\beta k_j.$$

$$\tau_p^{-1} = \frac{\pi}{2}\Omega_e\left(\frac{\mathcal{E}_{\rm tot}}{B_0^2/8\pi}\right)(q-1)k_{\rm min}^{q-1}.$$

$$D_{EE} = \frac{E^2}{2}\int_{-1}^1 d\mu\, D_{\mu\mu}(R_1-R_2^2).$$

$$R_1(\mu,p) = \frac{D_{pp}}{p^2D_{\mu\mu}},\quad R_2(\mu,p)=\frac{D_{p\mu}}{pD_{\mu\mu}}.$$

$$\frac{\partial N}{\partial t} = \frac{\partial^2}{\partial E^2}(D_{EE}N) + \frac{\partial}{\partial E}[(\dot{E}_{\rm L}-A)N] - \frac{N}{T_{\rm esc}} + Q$$

Diffusion **Loss and Acceleration** **Escape** **Source**

$$A(E) = \frac{dD_{EE}}{dE} + D_{EE}\frac{2\gamma^2-1}{(\gamma^2-1)\gamma mc^2}$$

Electron-ion collision

$$\dot{E}_{Li} = 2\pi r_0^2 m_e c^3 n_e\left(\frac{q_i}{e}\right)^2 \times \begin{cases} 2\sqrt{2}\beta^2\beta_{Te}^{-3}\ln\Lambda\left(\frac{3}{\pi}\right)^{1/2} & \text{for } \beta<\beta_{Te},\\ \beta^{-1}\ln\left(\frac{m_e^2c^2\beta^4}{\pi r_0 n_e\hbar^2}\right) & \text{for } 1\gg\beta>\beta_{Te},\\ \ln\left(\frac{m_e^2c^2\gamma^2}{2\pi r_0 n_e\hbar^2}\right) & \text{for } \frac{m_i}{m_e}\gg\gamma\gg 1,\\ \ln\left(\frac{m_e m_i c^2\gamma}{4\pi r_0 n_e\hbar^2}\right) & \text{for } \gamma\gg\frac{m_i}{m_e},\end{cases}$$

Time Scales

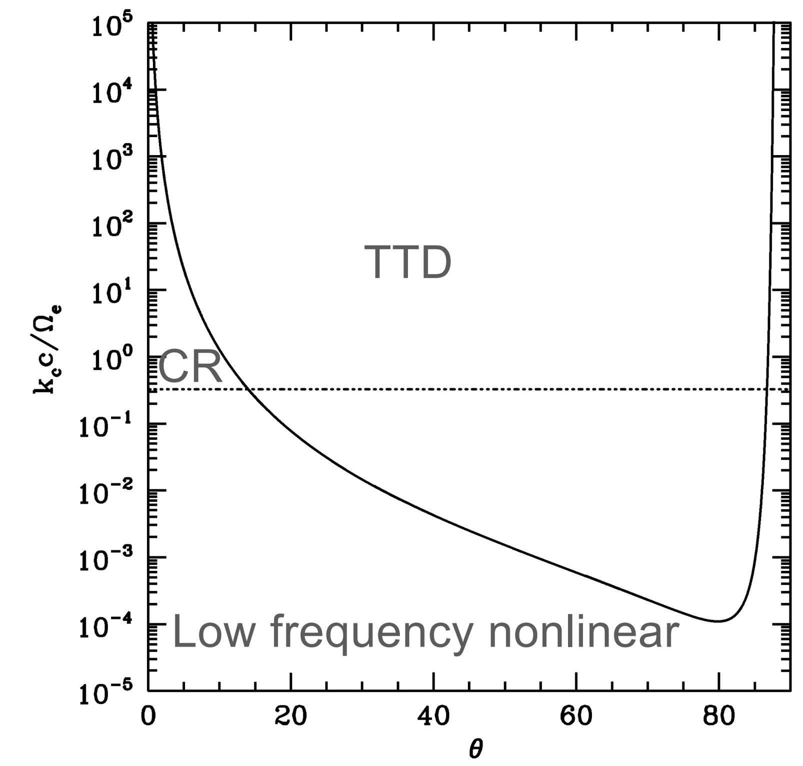
$$\tau_{\rm ac} = E^2/D_{EE}\qquad \tau_{\rm loss} = E/\dot{E}_{\rm L}$$

$$T_{\rm esc} = \frac{L}{\sqrt{2}v}\left(1+\frac{\sqrt{2}L}{v\tau_{\rm sc}}\right)\quad \tau_{\rm sc} = \frac{1}{2}\int_{-1}^1 d\mu\frac{(1-\mu^2)^2}{D_{\mu\mu}}$$

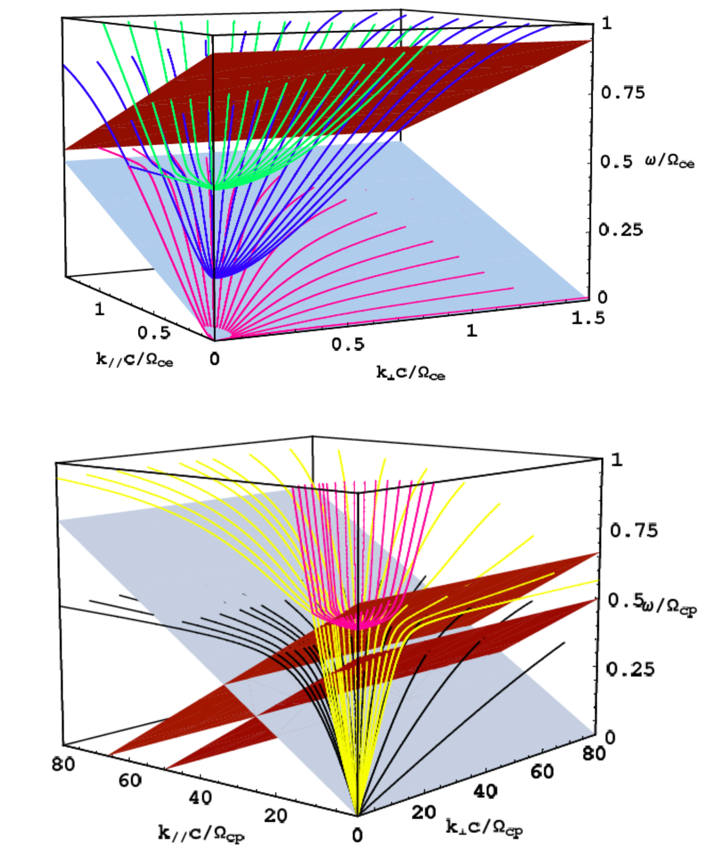
Proton-ion collision

$$\dot{E}_{Li} = 4\pi r_0^2 m_e c^3 n_p (q_i/e)^2 (m_e/m_p)\beta^{-1}\ln\Lambda.$$

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}W\right] - \Gamma(\mathbf{k})W - \frac{W}{T^W_{\rm esc}(\mathbf{k})} + \dot{Q}^W$$



Regimes of different interactions and damping via TDD



Dispersion relation in cold plasma and resonance condition

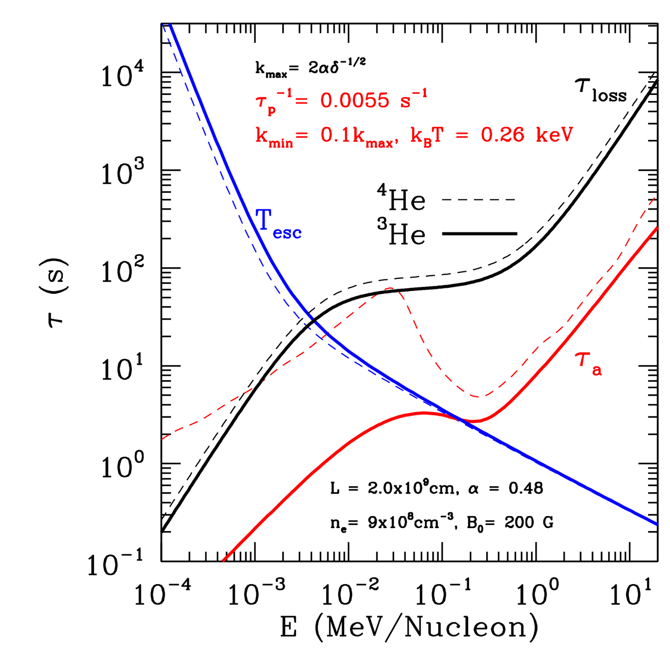
Wave Cascade and Damping

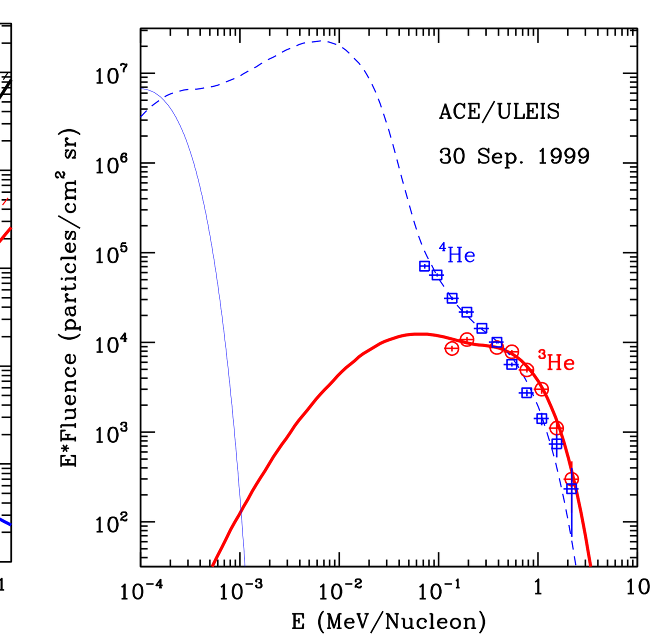
In general, waves are generated on large scale with relatively low frequencies and cascade into small scale high frequency regimes via nonlinear processes, where: oblique waves are damped via TTD; parallel waves are damped via CR; while perpendicular waves are damped via nonlinear processes [3, 8].

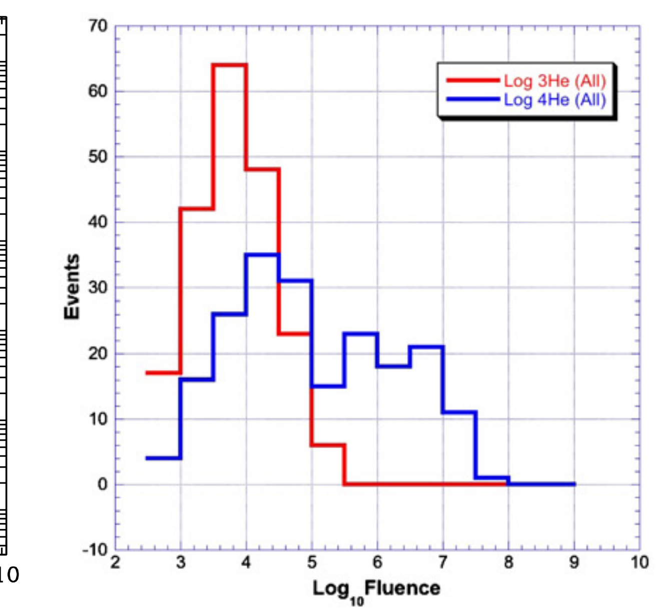
The nonlinear regime of the wave phase space (left) expands with the wave intensity. Overall particle acceleration will be less selective in larger events for the suppression of the CR regime, which explains their relatively weaker 3He enrichment.

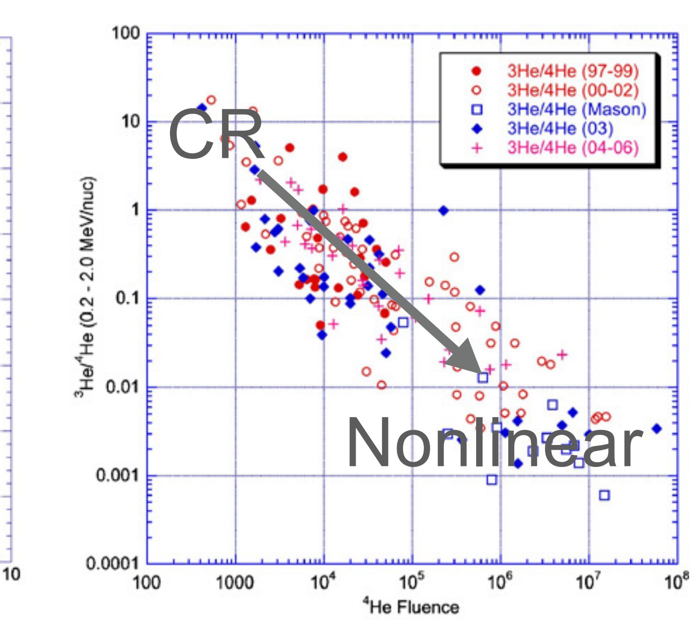
Selective Acceleration

3He enrichment is achieved via resonances with proton-cyclotron waves. While proton and 4He have much weaker energy gain via CR due to modification of the dispersion relation as background particles [6] and damping by the thermal background. The model predicts depletion of low-energy 3He giving rise to a flat spectrum toward low-energy [2] and an anti-correlation between 3He enrichment and 4He fluence, a measurement of flare amplitude [4].



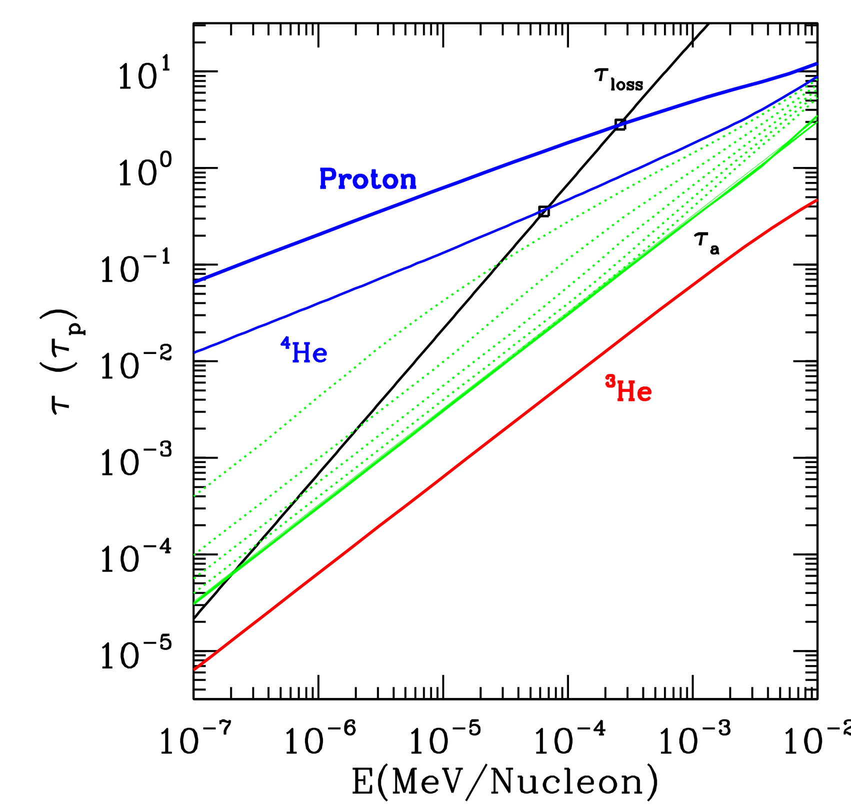


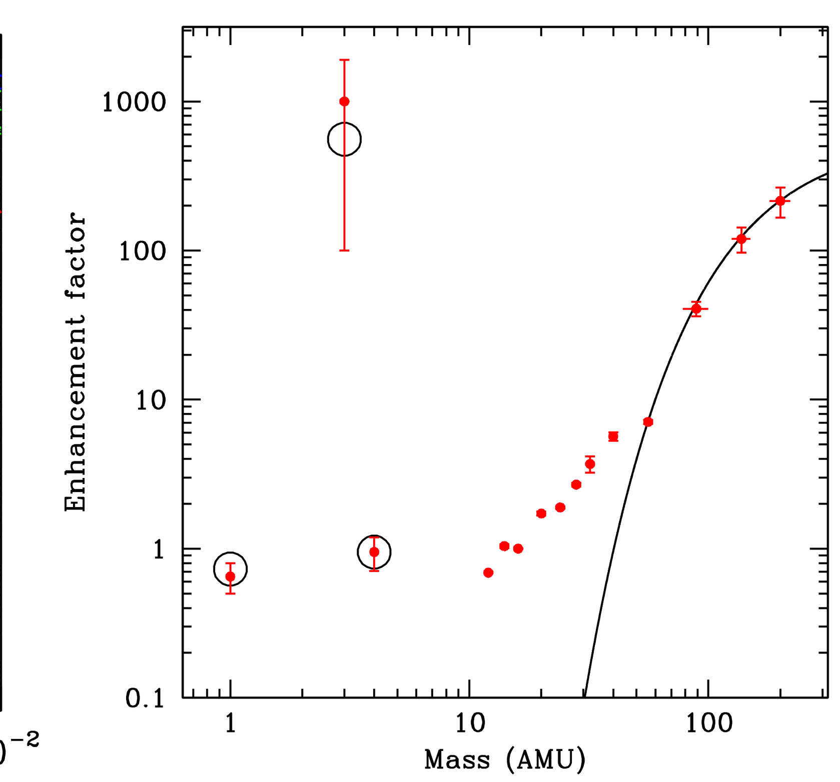




Heavy ion enrichment is less prominent than 3He [5] due to CR with low frequency MHD waves and collisional energy loss at low energies for their high charge.

The right panel for impulsive SEPs assumes that all ions are accelerated to the same velocity distribution due to chaotic particle orbits at the ion inertial scale of magnetic reconnection [7] and ions above an energy threshold are accelerated to high energy while all 3He are selectively accelerated.





References

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[2] Liu, Petrosian, & Mason 2006, ApJ 636 462;
[3] Jiang, Liu, & Petrosian. 2009, ApJ 698 163;
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