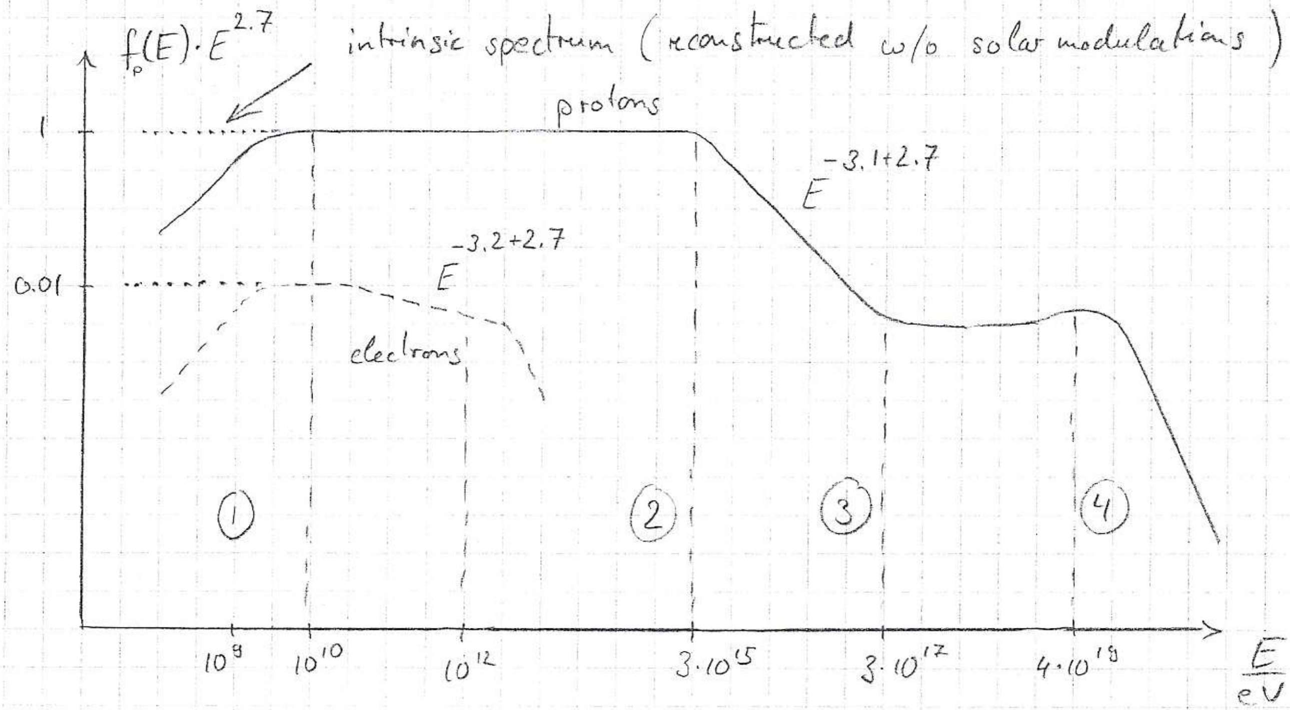
Lecture 8

1. Galactic Cosmic Rays

1.1. Cosmic ray protons: spectrum



- spectral features:

① solar modulation: the solar wind prevents low energetic charged particles from reaching the inner solar system due to interactions with the magnetic field in the solar wind which acts effectively as a mirror. The solar wind is a steady stream of magnetized plasma which the Sun emits in all directions and which is responsible for us being unable to observe ISM particles with energies $\lesssim 300$ MeV.

Protons with $E \gtrsim 10$ GeV are unattained, since their Larmor radius

$$r_L \equiv \frac{p_\perp c}{ZeB} \simeq \frac{2}{Z}\left(\frac{E}{10\,\mathrm{GeV}}\right)\left(\frac{B}{\mu G}\right)^{-1} \mathrm{AU}.$$

(2) Cosmic ray knee:

Interpretation: CRs up to the knee are accelerated by supernova remnants. Once, the Larmor radius of CRs matches the spatial extend of the shocked shell, that expand into the stellar wind, the acceleration efficience decreases and an energy cutoff develops. This knee should develop at fixed rigidity (= total momentum per unit charge) and amounts to

$$r_L \simeq 3\,pc \frac{E/Z}{3\cdot 10^{15}eV} \frac{B}{\mu G}, \qquad 1pc = 2\cdot 10^{5} AU$$

→ CRs at these energies can not be sufficiently isotropised and confined to the downstream regime of the shock which leads to an increase of their escape probability into the ISM; change in composition also observable! (Z increases for $E \gtrsim 3\cdot 10^{15} eV$)

(3) Cosmic ray ankle:

For energies $E \gtrsim 3\cdot 10^{17} eV$, the CRs cannot any more be confined to the galactic thin disk, since $r_L > 300\,pc = H$ and at $E > 3\cdot 10^{18} eV$, we observe extragalactic CRs ($r_L > 3\,kpc = H_{thick\ disk}$).

Evidence for change in composition and slope!

(4) Cosmic ray toe (GZK cutoff):

Photo-pion production possible in the rest frame of a CR proton of $E \sim 4\cdot 10^{19} eV$. $\lambda_{mfp}\big|_{GZK} \simeq 50\,Mpc$, which implies an anisotropy of arrival directions at these energies. HiRes and the Pierre Auger collaboration proved its existence last year with 5σ.

"Top-down" scenarios of decaying supermassive (hypothetical) particles (topological defects) with $Mc^2 > 10^{20}$ eV are now ruled out!

"Bottom-up" scenarios are now challenged to find an astrophysical explanation for the acceleration of these ultra-high energy cosmic rays.

- Presence of a "broken" power-law momentum spectrum

In Lecture 2, we demonstrated how diffusive shock acceleration can produce a power-law, if continuous momentum loss processes are too slow compared to the acceleration and escape processes.

- Cosmic ray isotropy

Scattering of CRs by low frequency MHD plasma waves guarantees near isotropy of CRs, because magnetic force of these waves is much larger than the electric force (Lecture 1).
If these waves are not present, freely streaming cosmic ray particles along the ordered B-field efficiently generate these waves.

1.2. Cosmic ray electrons

① CR electrons have a spectrum similar to that of protons for $E < 10\,\mathrm{GeV}$. This implies that their acceleration mechanism is similar if not identical.

② $E > 10\,\mathrm{GeV}$: IC and synchrotron losses lead to a steepening of the injected spectrum by one energy unit: $E^{-2.3} \rightarrow E^{-3.3}$ (Lecture 7)

③ This implies that the intrinsic (freshly injected) spectrum of galactic CR electrons + protons $\propto E^{-2.3}$ and suggests an energy dependent diffusion coefficient for CR protons of $\kappa \propto E^{-1/3}$ to explain the observed spectrum of CR protons of $E^{-2.7}$.

1.3. Proton to electron ratio: $\frac{n_p(\mathrm{GeV})}{n_e(\mathrm{GeV})} = 10\,\mathrm{GeV}$

① Maxwellian: $f_{th}(p)\,dp \propto p^2 e^{-\frac{E(p)}{kT}}\,dp$

$$f_{th}(E)\,dE \propto f[p(E)]\,\frac{dp}{dE}\,dE = p(E)^2 e^{-\frac{E}{kT}}\,\frac{dp}{dE}\,dE$$

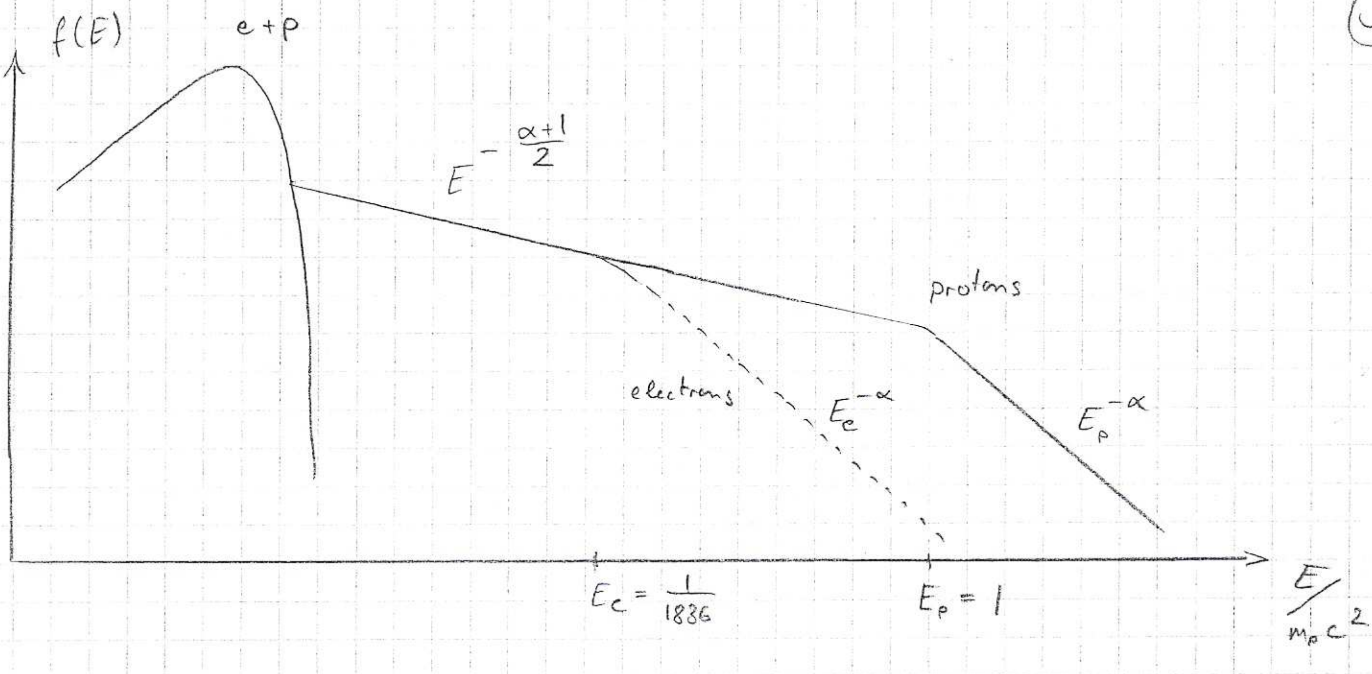
$$\overset{NR}{\propto} \sqrt{E}\,\exp\left(-\frac{E}{kT}\right) dE$$

$$\text{using} \quad E = \begin{Bmatrix} \frac{p^2}{2m} \\ pc \end{Bmatrix} \Rightarrow p = \begin{Bmatrix} \sqrt{2mE} \\ \frac{E}{c} \end{Bmatrix} \Rightarrow \frac{dp}{dE} \propto \begin{Bmatrix} E^{-1/2} \\ 1 \end{Bmatrix}$$

② Fermi I - power law: $f_{CR}(p)\,dp \propto p^{-\alpha}\,dp, \quad \alpha = 2.3$

$$f_{CR}(E)\,dE = f_{CR}[p(E)]\,\frac{dp}{dE}\,dE \propto p(E)^{-\alpha} \cdot \begin{Bmatrix} E^{-1/2} \\ 1 \end{Bmatrix} dE$$

$$\sim f_{CR}(E)\,dE = \begin{cases} E^{-\frac{\alpha+1}{2}}\,dE & \text{non-rel.} \\ E^{-\alpha}\,dE & \text{relativistic} \end{cases}$$



proton-to-electron ratio @ 1 GeV:

$$\frac{f_p(1)}{f_e(1)} = \frac{f_p(E_e)}{f_e(E_e)} \frac{\left(\frac{1}{E_e}\right)^{-\frac{\alpha+1}{2}}}{\left(\frac{1}{E_e}\right)^{-\alpha}} = \left(\frac{1}{E_e}\right)^{\frac{-\alpha-1+2\alpha}{2}} = E_e^{\frac{\alpha-1}{2}} = \left(\frac{1}{1836}\right)^{0.65} \simeq 0.01$$

2. Cosmic rays in clusters of galaxies

2.1. Sources of CRs:

- DSA at structure formation shocks, integrated over cosmic history
- Enrichment of ICM by galactic winds which advect CRs from SN remnants
- CR diffusion out of AGN, CRs are accelerated by means of DSA in "internal" shocks of the relativistic jet.

2.2. CR protons

① Timescales : $\tau_p\,(\gamma_p > 1) = \tau_{Hubble} \cdot \left(\frac{n}{10^{-2}\,cm^{-3}}\right)^{-1}$

② CRs are confined to cluster for $E < 10^{18}\,eV$. They accumulate a smooth distribution within a cluster.

⇒ need inelastic p-p process to study CR protons :

- radio emission by secondary electrons
- Xray emission by Compton-upscattering CMB photons off secondary electrons
- γ-ray emission from pion decay

2.3. CR electrons

① Time scales: $\tau_e\,(\gamma_e > 200) = 10^9\,yr \cdot \gamma_{200}^{-1}$, $\gamma_{200} = \frac{\gamma}{200}$

② Dominant point-like electromagnetic interactions:

<u>Sync:</u> $\nu_{sync} = \frac{3eB}{2\pi m_e c}\,\gamma^2 \simeq 1\,GHz \cdot \frac{B}{\mu G}\left(\frac{\gamma}{10^4}\right)^4$

<u>IC</u> : $h\nu_{IC} = \frac{4}{3}\,h\nu_{init}\,\gamma^2 \simeq 90\,keV\,\frac{\nu_{init}}{\bar{\nu}_{CMB}}\left(\frac{\gamma}{10^4}\right)^4$, $h\bar{\nu}_{CMB} = 0.66\,meV$

⇒ radio and hard X-ray emission

2.4 Cosmic rays and radiative processes – overview

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