Particle transport and stochastic acceleration in the giant lobes of Centaurus A

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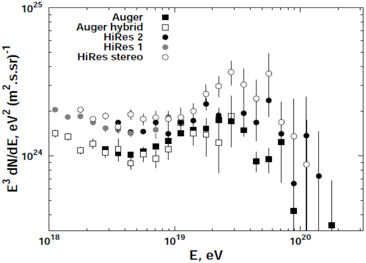
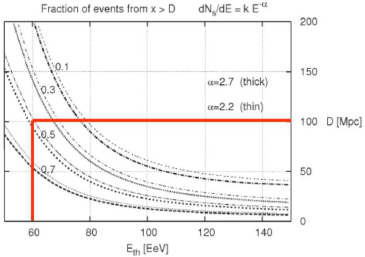
Outline

1. Radio galaxies and Centaurus A
2. GL Spectra
3. Transport in lobes
4. Stochastic acceleration in lobes
5. Conclusions

UHECR source/composition debate

- Source identification and composition intrinsically linked
- Non-complementary evidence on observed correlation and composition
- GZK pUHECR/NUHECR interaction with CMB-CIB
  - $p + \gamma \rightarrow p + e^+ + e^-$ (pair-production)
  - $p + \gamma \rightarrow p + \pi^0$ and $p + \gamma \rightarrow n + \pi^+$ (photo-pion interaction)
  - $(\mathrm{A,\ Z})\gamma \rightarrow \begin{cases} (\mathrm{A,\ Z}) + e^+ + e^- & \text{for } 10^{19.7}\,\mathrm{eV} < \mathrm{E}_{(\mathrm{A,\ Z})} < 10^{20.2}\,\mathrm{eV} \\ (\mathrm{A}-1,\ \mathrm{Z}) + n/p & \text{for otherwise (single nuc.).} \end{cases}$
  - $(\mathrm{A,\ Z})\gamma \rightarrow (\mathrm{A}',\ \mathrm{Z}') + (\mathrm{Z}-\mathrm{Z}')p + (\mathrm{A}-\mathrm{A}'+\mathrm{Z}-\mathrm{Z}')n$ (photo-dis.)
- Coincidentally similar energy cutoff p/NUHECR $\sim$ 100 Mpc (compatible with Auger, HiRes, TA)

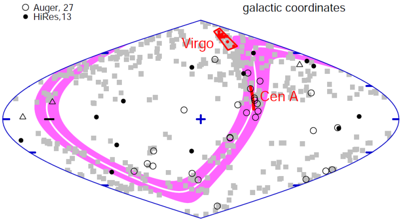


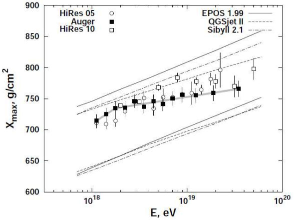


Cen A association

- 2007: $E > 57\,\mathrm{EeV}$ 19/27 (3σ) corr. within 3.1° of $d < 75\,\mathrm{Mpc}$ VCV AGN Auger Collaboration 2007
- 2009: 26/58 events corr. reduced to $< 1.7\sigma$ Auger Collaboration 2009
- Cen A: 12/58 within 18° (2.7 expected)
- Auger AGN correlation suggests pUHECR but...
- heavier composition also suggested by Auger
- HiRes does not find correlation w/ classes *or* LSS *nor* the signs of increasing mass (also TA?)

Proviso: results based on implementation of uncertain hadronic interaction models, different detectors, different hemispheres

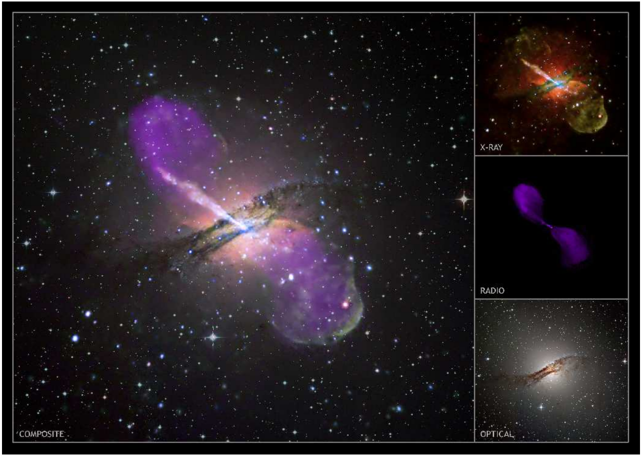




Heavy nuclei

- NUHECR composition - hadronic interaction models?
- Auger spatial correlation with LSS instead (not HiRes)?
  - eg. Centaurus supercluster (but not Virgo)
- Virgo deficit (heavy nuclei shifted by 20° to Cen A!? (Semikoz 2010)
  - require TA, JEM-EUSO
- Pe'er et al. (2009) suggest RQAGN as viable source if NUHECR

Centaurus A (NGC 5128)

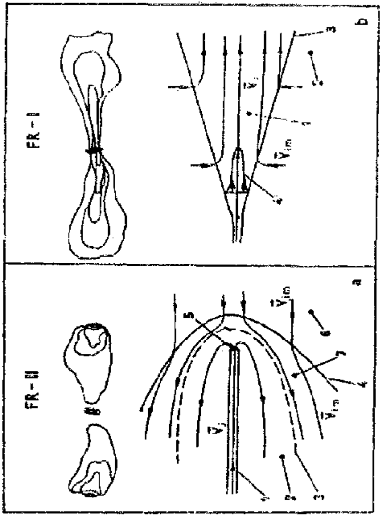


(X-ray - NASA, CXC, Kraft (CfA), et al; Radio - NSF, VLA, Hardcastle (U Hertf) et al; Optical - ESO, Rejkuba (ESO-Garch) et al.)

Given its particular significance, we focus on Cen A

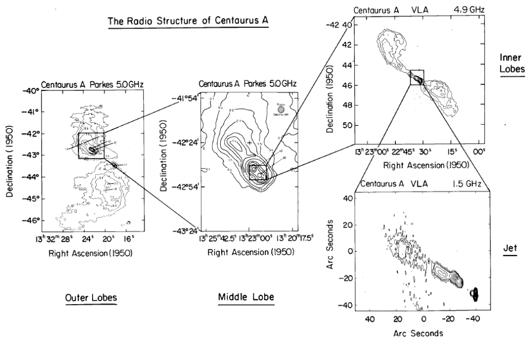
FR I versus FR II

- FR I (eg. Cen A)
  - More common and diverse than FR II
  - Subsonic RT unstable jets - no termination shock
  - Higher surface brightness close to core
  - Primary acceleration at core (electrostatic/centrifugal?)
  - Powered down FR II?
- FR II (eg. Cygnus A)
  - Supersonic collimated jet - termination shock
  - Highest surface brightness closest to hotspots
  - Primary acceleration at hotspots (first-order Fermi)

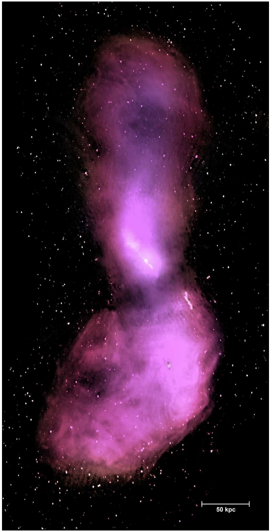


(Komissarov 1988)

Cen A Morphology



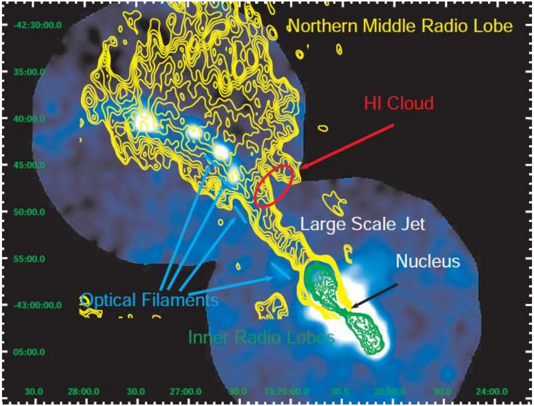
(Burns et al. 1983)



(Ilana Feain, Tim Cornwell & Ron Ekers (CSIROATNF))

d	3.4 Mpc	$P_{\rm jet}$	$\sim 6 \times 10^{42}$ erg/s
$(1'$	$= 1$ kpc)	$M_{\rm BH}$	$10^8\, M_{\rm sun}$
Radio	$8^\circ \times 4^\circ$	Acc.	$< 5^{-3}\, m_{\rm Edd}$
l_c	~ 10 kpc	Jet	$\sim 50^\circ$

Cen A giant lobe dynamical age



(Kraft 2009)

$u_{\mathrm{ij}} \sim 0.5\,c$ (Tingay 1998; Hardcastle 2003)

$u_{\mathrm{lsj}} \sim 2500\,\mathrm{km\,s^{-1}}$ (Burns 1983; Kraft 2009) $\tau_{\mathrm{lobes}} > 100\,\mathrm{Myr}$

$T_{\mathrm{ISM}} \sim 0.35\,\mathrm{keV}$ $\tau_{\mathrm{lobes}} > 100\,\mathrm{Myr}$ (Kraft 2003; Croston 2009)

Outline

GL Spectra

Observations in radio to gamma-ray constrain models of acceleration by dictating energies and localities of relativistic electrons in GLs.

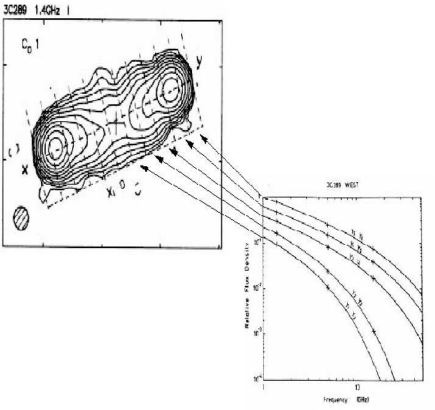
Electron radiative energy dissipation

- Synchrotron $\left(\frac{\nu_c}{\mathrm{GHz}}\right) \sim 0.016 \left(\frac{B \sin\theta}{\mu\mathrm{G}}\right) \left(\frac{E}{\mathrm{GeV}}\right)^2 \propto BE^2$
  $\nu_c \sim 100$ GHz for $E \sim 100$ GeV ($\gamma \sim 2 \times 10^5$) in $B \sim 1\mu$ G field
- $\left(\frac{\tau_{\mathrm{synch}}}{\mathrm{Myr}}\right) \sim 1060 \left(\frac{B \sin\theta}{\mu\mathrm{G}}\right)^{-\frac{3}{2}} \left(\frac{\nu_c}{\mathrm{GHz}}\right)^{-\frac{1}{2}} \propto B^{-2}E^{-1}$
  $\tau_{\mathrm{synch}} \sim 195$ Myr ($\tau_{\mathrm{synch}} \sim 20$ Myr at $E \sim 1$ TeV)
- $\nu_{\mathrm{IC}} \sim \gamma^2 \nu_{\mathrm{seed}}$ ($\sim 6 \times 10^{21}$ Hz for CMB)
- IC losses have same energy dependence as synch, $\propto U_B/U_{\mathrm{CMB}}$
- $\tau_{\mathrm{cool}} \sim \left(1 + \frac{U_{\mathrm{CMB}}}{U_B}\right)^{-1} \tau_{\mathrm{synch}}$
  $\tau_{\mathrm{cool}} \sim 18$ Myr ($U_B \sim 0.025\,\mathrm{eV\,cm^{-3}}$, $U_{\mathrm{CMB}} \sim 0.25\,\mathrm{eV\,cm^{-3}}$)

IC loss ~ 10 greater $\rightarrow$ order of magnitude dominance γ-ray emission

Radio Spectral Ageing

$\mathrm{d}E/\mathrm{d}t \propto E^2$ and $\nu_c \propto E^2 \rightarrow$ break



Spectral Ageing Models

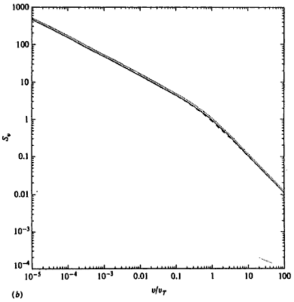
Tentative constraints on acceleration mechanism and efficiency.

Broken power law electron energy distribution $N(E) \propto E^{-p}$

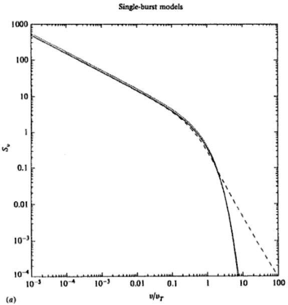
$$p = \begin{cases} 2\alpha_{\rm in} + 1 & \text{for} \quad E_{\rm min} \leq E < E_{\rm br} \\ a\alpha_{\rm br} + b & \text{for} \quad E_{\rm c} < E \end{cases}$$

- Continuous injection (CI) $a = 1$, $b = 1/2$ (Padcholczyk 1970)
- Kardashev-Pacholczyk (KP) μ fixed - $a = 4/3$, $b = 1$

  (Kardashev 1962; Pacholczyk 1970)
- Jaffe-Perola (JP) μ isotropization - exponential(Jaffe & Perola 1973)



(Hughes 1991)



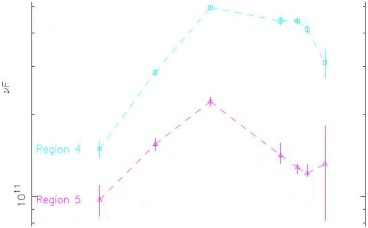
(Hughes 1991)

Cen A GLs: Five-year WMAP Hardcastle et al. 2008

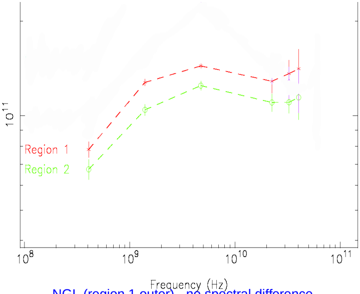
- SED breaks: 1 - 5 GHz for NGL; 5 - 20 GHz for SGL
- NGL well fit by CI with $E_{\rm max} = 1 \times 10^{11} - 4 \times 10^{11}$ eV
- SGL well fit by JP - last injection $\sim$ 30 Myr

Reacc. in NGL and dormancy in SGL suggested.

NB: adiabatic expansion shifts ν and F uniformly;
form dependent on $\langle B \rangle$, $\langle B^2 \rangle$, inj process, and μ.



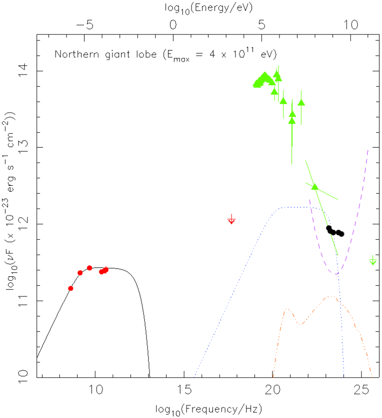
SGL (region 5 outer) - 5 steeper $\longrightarrow$ spectral ageing



NGL (region 1 outer) - no spectral difference

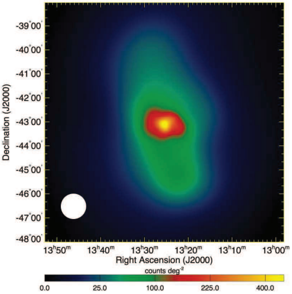
Predictions for Fermi LAT

NGL: CI model fit to $E_{\max} = 4 \times 10^{11}$ eV and $B = 3\mu$ G



Radio data points are sum of measurements from the ground-based radio maps and WMAP data. Solid line shows the predicted synchrotron emission for the specified electron spectrum, the dotted line shows the IC prediction for CMB photons. (Hardcastle et al. 2008)

Fermi LAT

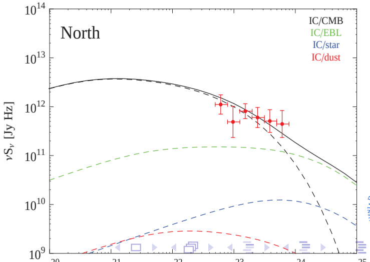


- GLs of Cen A ten times more luminous in gamma than radio
- First *direct* evidence of $> 10^{11}$ eV electrons in GLs
- $\rightarrow$ *in-situ* reacceleration or fast-streaming (super Böhm)

Model: $n_e = \begin{cases} k_e \gamma^{-s_1} & \gamma_{\rm min} \le \gamma < \gamma_{\rm br} \\ k_e \gamma_{\rm br}^{s_2 - s_1} \gamma^{-s_2} e^{-\gamma/\gamma_{\rm max}} & \gamma \ge \gamma_{\rm br} \end{cases}$

Constrained by radio (WMAP):

$E_e \sim 10^{11} - 10^{12}$ eV and $B \lesssim 1\,\mu$G



GL Spectra

Cutoff in EED consistent with $E_{\rm max} \lesssim 1$ TeV with $B \lesssim 1\,\mu$G.

Based on source age arguments, fast-transport and/or local acceleration may be relevant.

Outline

Motivation

E eV	γ	ν_c Hz	r_g pc	ρ Myr	τ_{cool} Myr
10^8	1.96×10^2	1.07×10^5	1.08×10^{-7}	1.08×10^{-11}	17100
10^{10}	1.96×10^4	1.07×10^9	1.08×10^{-5}	1.08×10^{-9}	171
10^{12}	1.96×10^6	1.07×10^{13}	1.08×10^{-3}	1.08×10^{-7}	1.71

RIGIDITY: $\rho \equiv r_g / l_c$

($B = 1\,\mu$G, $l_c = 10$ kpc, $U_{CMB} \sim 0.25\,\mathrm{eV\,cm^{-3}}$)

Highest observed synchrotron electrons have ultra-low rigidity - not Böhm diffusive

Study *static* fields initially.

Quasilinear Theory

$\mathbf{B} = B_0\hat{\mathbf{z}} + \mathbf{B}_1$ where $b \equiv \left[\frac{<B_1^2>}{<B_0^2>}\right]^{1/2} \ll 1$

Two components to particle transport:

- Field line wandering => $\frac{<\Delta^2 x>}{2\Delta s} = D_M = \frac{b^2\lambda_{\parallel}^{corr}}{4}$
- Scattering => $\kappa_{\parallel} = \kappa_B/\epsilon \quad \kappa_{\perp} = \epsilon\kappa_B/(1+\epsilon)$

Transport regimes:

- Ballistic => $D_{\perp} \rightarrow \kappa_{\perp} + vD_M$
- Collisional ($\Lambda \lesssim 1$) => $D_{\perp} \rightarrow \kappa_{\perp}$ and $D_{\parallel} \rightarrow \kappa_{\parallel}$
- Compound ($\Lambda \gg 1$) => initially subdiffusive

See Duffy et al. A&A 1995

$$\kappa_B \equiv \frac{\gamma v^2 mc}{3eB}$$

$$\epsilon = \nu_{coll}/\omega_g$$

$$\Lambda \equiv \frac{b^2\lambda_{\parallel}^{corr}}{\sqrt{2\epsilon}\lambda_{\perp}^{corr}}$$

$$D_{\perp} \equiv \frac{<\Delta^2 x>}{2\Delta t}$$

$$D_{\parallel} \equiv \frac{<\Delta^2 z>}{2\Delta t}$$

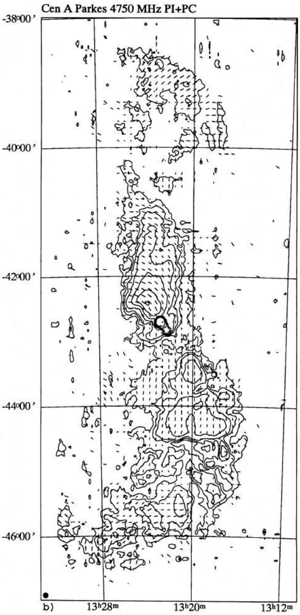
Transport

Theory does *not* offer robust model of transport in GL environment.

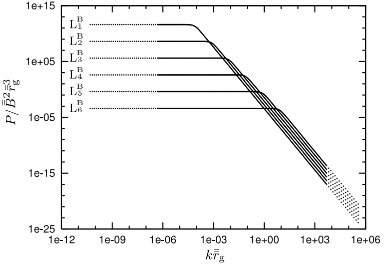
Numerical models

- $\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}\tau} = \frac{e}{m}\mathbf{u} \times \mathbf{B}$
  (static **B** - energy conserved)
- Disordered field ($\langle B \rangle >= 0$) (Junkes 1993)
- $\mathbf{B} = \int \mathrm{d}^3\mathbf{k}\, \mathbf{A}_\mathbf{k} \exp(i\mathbf{k} \cdot \mathbf{r})$
- $\nabla \cdot \mathbf{B} = 0$
  maintained via $\mathbf{k} \cdot \mathbf{A}_\mathbf{k} = 0$
- $\langle \mathbf{A}_\mathbf{k} \cdot \mathbf{A}^*_{\mathbf{k}'} \rangle = P(\mathbf{k})\delta(\mathbf{k} - \mathbf{k}')$
  $\mathbf{A}_\mathbf{k}$ statistically independent, field homogeneous and Gaussian
- Continuous functional form

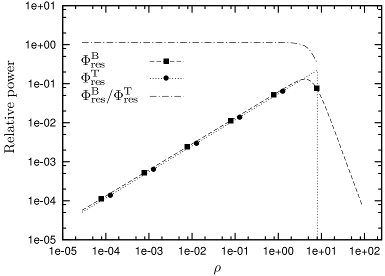
(Giacalone & Jokipii 1999)



Field characteristics



Broken power-law modes

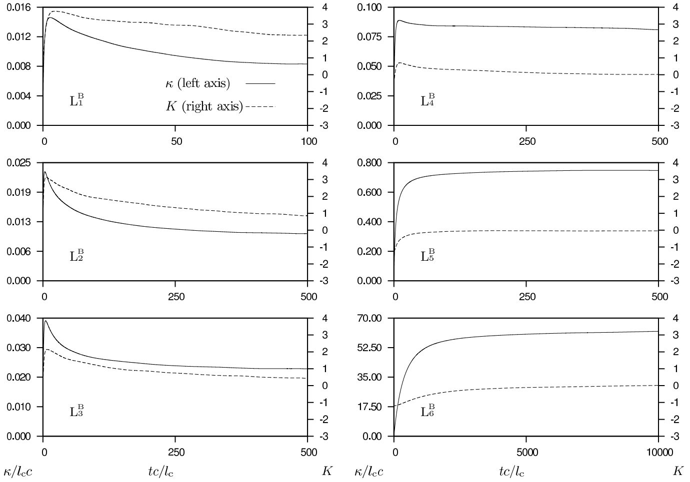


Resonant scale relative power

- $\Phi_{\rm res} = \dfrac{k_{\rm res}^3 P(k_{\rm res})}{3\int {\rm d}k\, k^2 P(k)}$
- Running kurtosis: $K(t) \equiv \frac{1}{3}\left(\frac{\langle\Delta_x^4\rangle}{\langle\Delta_x^2\rangle^2} + \frac{\langle\Delta_y^4\rangle}{\langle\Delta_y^2\rangle^2} + \frac{\langle\Delta_z^4\rangle}{\langle\Delta_z^2\rangle^2}\right) - 3$
- Running diffusion: $\kappa(t) \equiv \dfrac{\langle\Delta_x^2\rangle + \langle\Delta_y^2\rangle + \langle\Delta_z^2\rangle}{6t}$

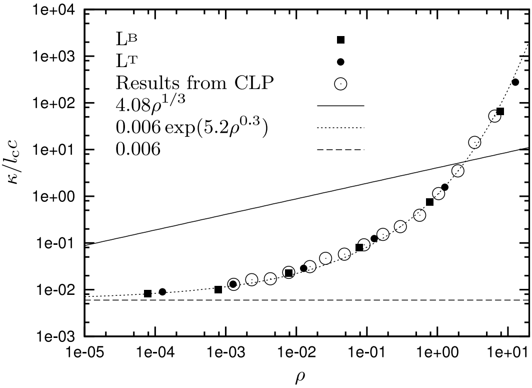
Particle Transport

Running diffusion and kurtosis coefficients



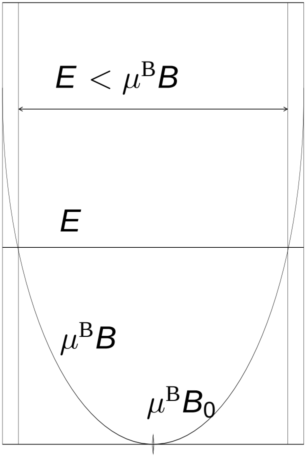
Particle Transport

Comparison with diffusion coefficients from various sources



Speculative model

- Assume injection of energetic particles at B_0 with single pitch angle α
- First invariant of the motion μ^{B} is associated with the cyclotron motion of the electron about a field line
  $\mu^{\mathrm{B}} = \frac{p_\perp^2}{2m_0B_0} = \gamma^2\mu^{\mathrm{B}}_{\mathrm{ref}} \qquad \left(\mu^{\mathrm{B}}_{\mathrm{ref}} \approx \frac{m_0c^2\sin^2\alpha}{2B_0}\right)$
- Mirror point $B \approx \gamma^{-2}(\frac{E}{\mu^{\mathrm{B}}_{\mathrm{ref}}}) = \gamma^{-1}(\frac{m_0c^2}{\mu^{\mathrm{B}}_{\mathrm{ref}}})$
- Penetration depth *increases* with falling rigidity for fixed pitch
  $\rightarrow$ stochastic bottle scale $\propto \rho^{-\alpha}$
- Variability in μ^{B} ($\sim r_{\mathrm{g}}$ hops via resonant $\sim k_{\mathrm{res}}$ scattering)
  $\rightarrow$ postulate reflections $\propto \rho^{-\alpha}$
- Under this description $\kappa \propto 1$



Implications for Electron transport

For $l_c = 10\,$kpc and $E = 10^8,\ 10^{10},\ 10^{12}$ eV

- $\tau_{\rm res}^{\rm Bhm} = 9.06 \times 10^{10},\ 9.06 \times 10^8,\ 9.06 \times 10^6$ Myr ($\tau_{\rm res}^{\rm Bhm} = 3L^2/\rho l_c c$)
- $\tau_{\rm res}^{\rm qlt} = 362,\ 77.9,\ 16.8$ Myr ($\tau_{\rm res}^{\rm qlt} = 0.245L^2/\rho^{1/3} l_c c$)
- Observed transport $\sim$ independent of ρ
- Diff. time over l_c: $\tau_{\rm diff} = \left(\frac{l_c}{c}\right)\left(\frac{\kappa}{l_c c}\right)^{-1}$
- $\tau_{\rm diff} = 5.42,\ 5.38,\ 5.21$ Myr
- $\tau_{\rm res} = 54.2,\ 53.8,\ 52.1$ Myr ($\tau_{\rm res}/\tau_{\rm dyn} \gtrsim 0.5$)
  $L \sim 100$ kpc, $\tau_{\rm dyn} \sim 100$ Myr ($V_{\rm expansion} \sim 0.256\, l_c$/Myr)
- Effective replenishment for $E \lesssim 10^{11}$ eV (unlike Böhm):
  $\tau_{\rm res} \lesssim \tau_{\rm dyn}$ *and* $\tau_{\rm res} \lesssim \tau_{\rm pp}$ $\quad\rightarrow\quad$ $\sim$ continuous injection
- No need to appeal to reacceleration

Proton transport

- $\nu_{\rm c} \sim 6.04 \times 10^{18} \left(\frac{E}{10^{20}\,\rm eV}\right)^2 \left(\frac{B}{1\,\mu\rm G}\right)$ Hz
  - drowned by IC X-ray emission
- $\tau_{\rm synch} \sim 1.4 \times 10^6 \left(\frac{E}{10^{20}\,\rm eV}\right)^{-1} \left(\frac{B}{1\,\mu\rm G}\right)^{-2}$ Myr (Aharonian 2002)
- $pp \rightarrow \pi \rightarrow e^+e^-\gamma$
  $\tau_{\rm pp} \sim 1.7 \times 10^6 \left(\frac{n_{\rm th}}{10^{-4}\,\rm cm^{-3}}\right)^{-1}$ Myr (Aharonian 2002)
  - $n_{\rm th} = 10^{-4}\,\rm cm^{-3}$ is *upper bound* on cold gas

E eV	γ	$\nu_{\rm c}$ Hz	$r_{\rm g}$ kpc	ρ	$\tau_{\rm synch}$ Myr	$\tau_{\rm pp}$ Myr
10^{14}	1.07×10^5	6.04×10^6	1.08×10^{-4}	1.08×10^{-5}	1.4×10^6	1.7×10^6
10^{16}	1.07×10^7	6.04×10^{10}	1.08×10^{-2}	1.08×10^{-3}	1.4×10^4	1.7×10^6
10^{18}	1.07×10^9	6.04×10^{14}	1.08×10^0	1.08×10^{-1}	1.4×10^2	1.7×10^6
10^{20}	1.07×10^{11}	6.04×10^{18}	1.08×10^2	1.08×10^1	1.4	1.7×10^6

Proton residence time

For $l_\mathrm{c} = 10\,\mathrm{kpc}$ and $E = 10^{14}, 10^{16}, 10^{18}, 10^{20}\,\mathrm{eV}$

- $\tau_\mathrm{res}^\mathrm{Bhm} = 9.06 \times 10^4, 9.06 \times 10^1, 9.06 \times 10^0, 9.06 \times 10^{-2}$ Myr
  ($\tau_\mathrm{res}^\mathrm{Bhm} = 3L^2/\rho l_\mathrm{c} c$)
- $\tau_\mathrm{res}^\mathrm{qlt} = 3.62, 0.779, 0.168, 0.0362$ Myr
  ($\tau_\mathrm{res}^\mathrm{qlt} = 0.245 L^2/rho^{1/3} l_\mathrm{c} c$)
- Diffusion time $\tau_\mathrm{diff} \sim \left(\frac{l_\mathrm{c}}{c}\right)\left(\frac{\kappa}{l_\mathrm{c} c}\right)^{-1}$ (time to diffusively traverse l_c)
- $\tau_\mathrm{diff} = 4.59, 2.78, 3.78 \times 10^{-1}, 1.33 \times 10^{-4}$ Myr
- $\tau_\mathrm{res} \sim 45.9, 27.8, 3.78, 0.00133$ Myr
  $L \sim 100\,\mathrm{kpc}$, $\tau_\mathrm{dyn} \sim 100\,\mathrm{Myr}$ ($V_\mathrm{expansion} \sim 0.256\,l_\mathrm{c}/\mathrm{Myr}$)
- Effective replenishment of lobe by energetic particles:
  $\tau_\mathrm{res} \lesssim \tau_\mathrm{dyn}$ *and* $\tau_\mathrm{res} \lesssim \tau_\mathrm{sync}$
- No need to appeal to reacceleration for $E \lesssim 10^{19}$ eV

Transport

Fast-streaming appears to be significant for electron transport in lobes.

Replenishment of $\lesssim$ TeV electrons compatibible with Fermi LAT observations of GLs.

Transport time of order GL lifetime or less for protons $\lesssim 10^{19}$ eV.

Outline

Stochastic acceleration

Have considered static fields in previous discussion. Moving and counter-moving fluctuations on gyroscale lead to Fermi-type acceleration process.

Fermi II acceleration in radio lobes

Mean free path

$$L \approx \frac{B_0^2}{\delta B^2} \left(\frac{r_g}{\lambda_{\rm max}} \right)^{1-q} r_g$$

Systematic acceleration timescale (quasi-linear theory)

$$t_{\rm acc} = \frac{p^2}{D(p)} \approx \beta_{\rm A}^{-2} \frac{L}{c} \propto p^{2-q} \qquad \left(t_{\rm acc} \propto p^2 \text{ for rigidity} > 1\right)$$

Highest energy protons resonate with $r_{\rm g} \sim \lambda_{\rm max}$ at about an order of magnitude down from the system size ~ 100 kpc

Canonical values for lobe:
$n_{\rm p} \sim 10^{-4}\,{\rm cm}^{-3}$, $B_0 \sim 1\,\mu{\rm G} \Rightarrow \beta_{\rm A} \approx 7.5 \times 10^{-4}$

So $t_{\rm acc}$ longer than Hubble time unless $\beta_{\rm A} \gtrsim 0.1$.

Numerical simulation

Motivation:

- Quasi-linear analysis requires $U_{\rm turb} \ll U_B$ and 1D field.
- Require (numerical) validation/extension of results within/beyond these constraints.
- Efficient Fermi II reported in the literature (Fraschetti & Melia 2008)

Two classes of simulation considered:

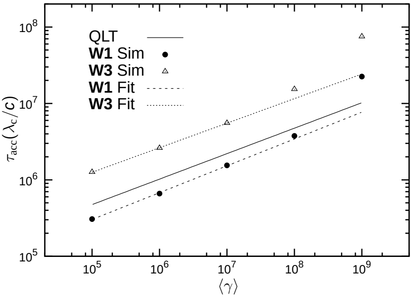
- $\beta_{\rm A} \ll 1$: early-time snapshots of diffusion δ-function momentum distributions
- $\beta_{\rm A} \lesssim 1$: direct simulation (eg. $\langle\gamma\rangle = 10^5$ to 10^9 within 4×10^8 gyroperiods)

Pre-acceleration process to lift from thermal pool missing: sample range $\langle\gamma\rangle = 10^5$ to 10^9.

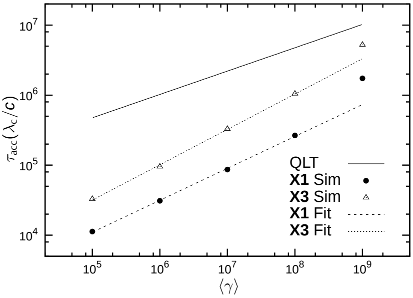
Need to be careful to maintain $E.B = 0$ to avoid unintended secular acceleration - simple lorentz transformation of Fourier B-modes inadequate.

Non-relativistic wave speed

Acceleration $\tau_{\rm acc}$ as a function of energy derived from best fits of Gaussian profiles to the std. dev. of the momentum distributions via γ_0^2/D_p where $D_p \equiv \langle \Delta\gamma^2 \rangle / 2\Delta t$.



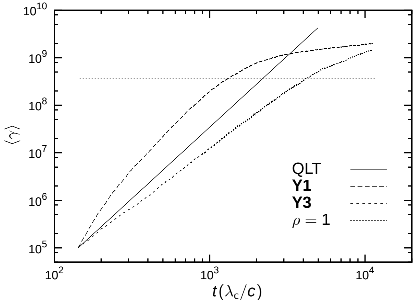
Weak turbulence.



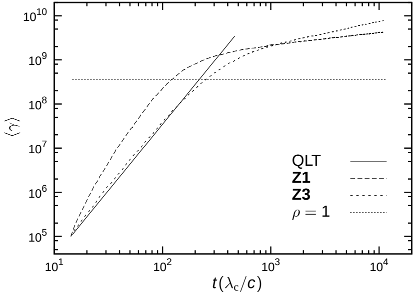
Strong turbulence.

Weakly relativistic wave speed

Mean energy against time for ensembles of 510 particles injected at $\gamma_0 = 10^5$.



Weak turbulence.



Strong turbulence.

Fermi II in GLs

From models of observations from Fermi LAT and others, $B \lesssim 1\,\mu$G and $E_c \lesssim 10^{12}$ eV.

If stochastic acceleration is responsible for *in-situ* reacceleration of electrons can infer a required $n_{\rm p} \approx 10^{-7}{\rm cm}^{-3}$ and hence $\beta_A \approx 0.02$ and $t_{\rm acc} \sim 100$ Myr for 10^{18} eV protons.

Improbable as primary accleration mechanism *but* may offer ideal reservoir for shear acceleration to highest energies.

Outline

Conclusions

- Cen A focal point of question over UHECR source, need better data/models
- Fast streaming may offer explanation of Fermi-LAT observations
- Stochastic acceleration unlikely to validate GLs as accelerators unless number density orders of magnitude lower than accepted upper bound...
- *but* may offer reservoir of preaccelerated particles for secondary acceleration
- Until more data is available, the only thing we can really say is Cen A is an interesting object for UHECR physicists.