Collective Escape of Cosmic Rays from their Acceleration Sites

Mikhail Malkov

UCSD

Collaborators: F. Aharonian, P. Diamond, I.Moskalenko and R. Sagdeev

Outline

1. Why CR Escape is important
   - Observational significance of CR escape
   - The role of escape in acceleration theory
   - Escape and proof of SNR origin of CR
2. Approaches to CR escape from accelerators
   - TP/self-confinement
3. Formulation of the Problem/Technique
   - Geometry/Equations
4. Results/Discussion of Observations/Summary
   - Self-similar solution/SNR W44

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Understanding accelerator by observing CR escape

- nearby molecular clouds (MC) illuminated by escaping CR probe accelerator (e.g. SNR)
- escape spectrum may considerably deviate from the source spectrum (source reconstruction problem)
- escape geometry is complicated (field aligned vs isotropic)
- morphology of emission from SNR dense gas surroundings probe magnetic field configuration around the source
- calculation of flux of escaping CRs, understanding geometry of escape provide access to (indirect) source calorimetry by measuring emission flux from illuminated MC

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CR escape/confinement and diffusive shock acceleration (DSA) theory

- CR escape/confinement is an integral, but poorly understood, part of acceleration theory
- strongly influences the spectrum, particularly cut-off energy
- as the DSA[1] is based on **self-confinement** the escape theory must also be
- escaping particles drive (Alfvén) waves that slow down the escape
- the level of self-excited waves is orders of magnitude higher than the ISM background turbulence level at relevant scales
- test particle escape theory is irrelevant near the accelerator where $\delta B \gg \delta B_{\rm ISM}$

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[1] Bell's talk on Monday, Bykov's this morning other talks this session

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CR-SNR connection

- electrons are known to be accelerated in SNR
- protons should be accelerated by the same mechanism in much larger amounts but radiatively poorly expressed
- visibility of CR protons depends on environment (dense gas required for pp collisions and detectable γ-emission) and their escape into this environment
- without understanding CR escape it is hard to disentangle $pp \to \pi^0 \to \gamma$ channel from electron inverse Compton emission and to proof the SNR origin of CR protons

- electrons are parasitically confined by proton generated waves and (modulo wave polarization[2]) are transported similarly to the protons of the same rigidity

- however, different targets for γ production: gas/photons: magnetic connectivity of gas with the CR source should be instrumental in $e - p$ disentangling

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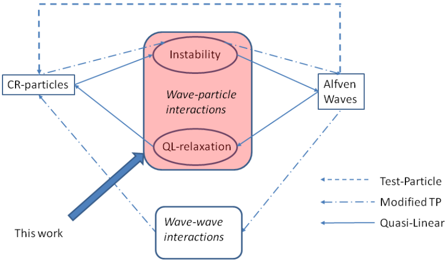
From test particle (TP) scattering to self-confinement



Three levels of treatment of CR escape/propagation

- CR diffusion in preexisting ISM turbulence
- CR diffusion in nonlinearly evolving turbulence
- quasi-linear relaxation of localized CR cloud on self-generated waves

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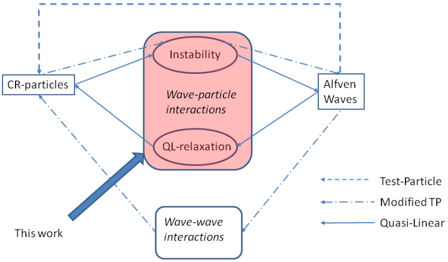

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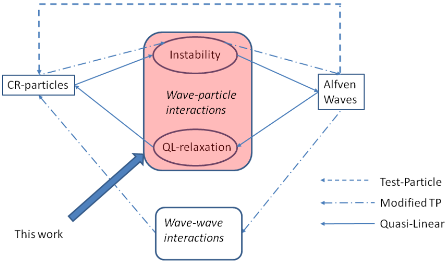

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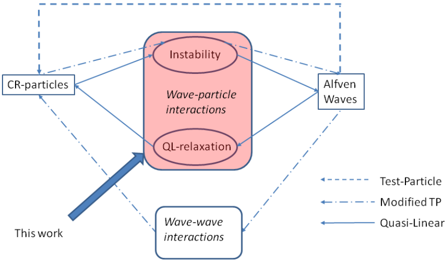

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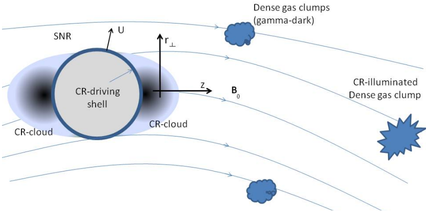
Problem setting/geometry



CR escape along MF from two polar cusps of SNR

- CR diffuse along MF
- generate Alfvén waves that suppress diffusion
- to obtain CR distribution both processes are treated self-consistently
- result will determine MC emissivity

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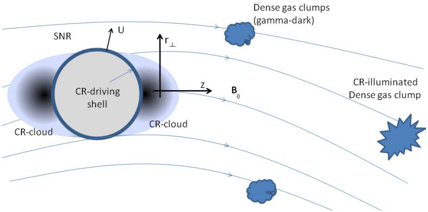

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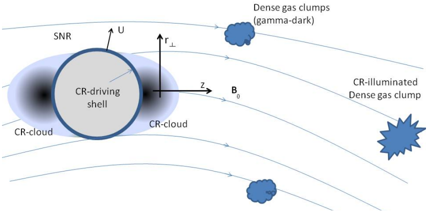

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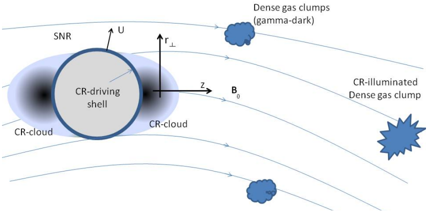

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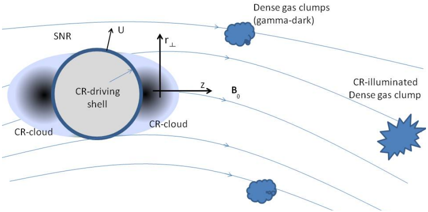

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- CR propagation in self-excited waves

$$\frac{d}{dt}P_{\mathrm{CR}}(p) = \frac{\partial}{\partial z}\frac{\kappa_{\mathrm{B}}}{I}\frac{\partial P_{\mathrm{CR}}}{\partial z}$$

$P_{\mathrm{CR}}(p)$ -partial pressure, $I(p)$ -wave energy, resonance $kp = eB_0/c$, $d/dt = [\partial/\partial t + (U + C_{\mathrm{A}})\partial/\partial z]$

- Wave generation by ∇P_{CR} associated with the CR pitch-angle anisotropy

$$\frac{d}{dt}I = -C_{\mathrm{A}}\frac{\partial P_{\mathrm{CR}}}{\partial z} - \Gamma I$$

- QL integral

$$P_{\mathrm{CR}}(z,t) = P_{\mathrm{CR0}}(z') - \frac{\kappa_{\mathrm{B}}}{C_{\mathrm{A}}}\frac{\partial}{\partial z}\ln\frac{I(z,t)}{I_0(z')}$$

$z' = z - (U + C_{\mathrm{A}})t$

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Reduction of Equations

- CR/Alfven wave coupling

$$\frac{\partial W}{\partial t} - \frac{\partial}{\partial z}\frac{1}{W}\frac{\partial W}{\partial z} = -\frac{\partial}{\partial z}\mathcal{P}_0(z)$$

$W = \frac{C_{\mathrm{A}}\, a(p)}{\kappa_{\mathrm{B}}(p)} I$ -dimensionless wave energy, $d/dt \approx \partial/\partial t$, $\mathcal{P}_0$-initial CR distribution, $|z/a| < 1$

- Self-similar solution in variable $\zeta = z/\sqrt{t}$, $W(z,t) = w(\zeta)$ for $|z| > a$, outside initial CR cloud

$$\frac{d}{d\zeta}\frac{1}{w}\frac{dw}{d\zeta} + \frac{\zeta}{2}\frac{dw}{d\zeta} = 0$$

- solution depends on integrated CR pressure in the cloud and background turbulence level $W_0 \ll 1$.

$$\Pi = \int_0^1 \mathcal{P}_0 dz \gg 1$$

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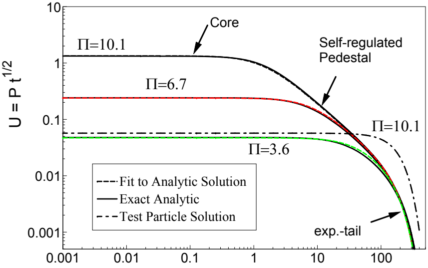
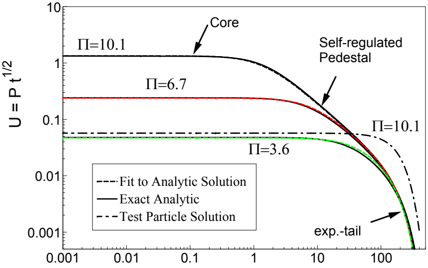


Self-confinement vs test-particle escape, $\sqrt{t}\mathcal{P}_{CR}$ vs $z/\sqrt{t}$ for different initial partial pressure parameters Π

Comparing and Contrasting with conventional TP predictions:

- considerable delay of CR escape
- narrower spatial distribution of CR cloud
- presence of extended self-similar, $\mathcal{P} \propto 1/z$ region

CR self-similar distribution



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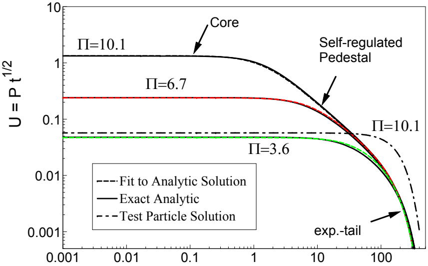

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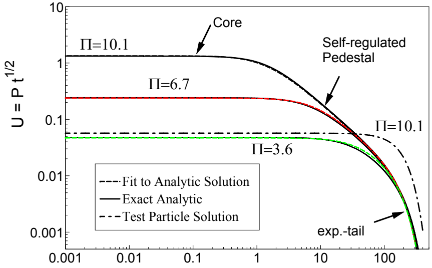

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- CR partial pressure (found in closed but implicit form) is well approximated by:

$$\sqrt{t}\mathcal{P} = 2\left[\zeta^{5/3} + (D_{\mathrm{NL}})^{5/6}\right]^{-3/5} e^{-W_0\zeta^2/4}$$

- particle diffusivity is strongly suppressed by **self-confinement** effect:

$$D_{\mathrm{NL}} = \frac{2}{V_0^2} D_{\mathrm{ISM}} e^{-\Pi}, \quad V_0 \sim 1$$

- as integrated CR pressure parameter is typically large:

$$\Pi \simeq 3 \frac{C_{\mathrm{A}}}{c} \frac{a(p)}{r_{\mathrm{g}}(p)} \frac{\bar{P}_{\mathrm{CR}}(p)}{B_0^2/8\pi} \gg 1$$

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CR Escape: Energy Spectrum

- CR partial pressure for $\delta B_{\mathrm{ISM}} \ll B_0$:

$$\mathcal{P} \approx 2\left\{z^{5/3} + \left[D_{\mathrm{NL}}(p)\, t\right]^{5/6}\right\}^{-3/5} \quad \Rightarrow \quad f_{\mathrm{CR}} \propto \kappa_{\mathrm{B}}\, p^{-4}/az$$

- for $a \propto \kappa_{\mathrm{B}}$ the spectrum is DSA like (evenly distributed partial pressure, wave generation takes care of that!)

$$f_{\mathrm{CR}} \propto p^{-4} \quad \mathit{where} \quad D_{\mathrm{NL}}(p) < z^2/t$$

- at $p = p_{\mathrm{br}}$, where $D_{\mathrm{NL}}(p_{\mathrm{br}}) = z^2/t$, spectrum incurs a break
- if $D_{\mathrm{NL}} \propto p^{\delta}$ near $p \sim p_{\mathrm{br}}$, break has index $\delta/2$
- δ determined by $D_{\mathrm{ISM}}(p)$ and CR pressure $\Pi(p)$
- $\exp(-\Pi) \propto p^{-\sigma}$, $D_{\mathrm{ISM}} \propto p^{\lambda}$ at $p \sim p_{\mathrm{br}}$, so that $\delta = \lambda - \sigma$
- $\delta > 0$: $\mathcal{P}$ is flat for $p < p_{\mathrm{br}}$ steepens to $p^{-\delta/2}$ at $p = p_{\mathrm{br}}$
- $\delta < 0$: $\mathcal{P}$ raises as $p^{-\delta/2}$ for $p < p_{\mathrm{br}}$ and flat for $p > p_{\mathrm{br}}$

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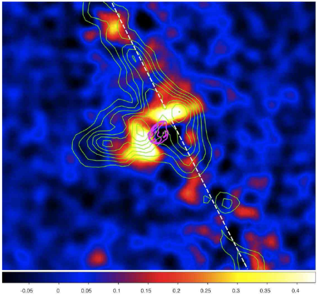
Recent observations



Fermi-LAT γ-image of SNR W44, *Uchiyama et al 2012*

- central source (magenta radio image) emission is masked
- bi-polar morphology of escaping CR is clearly seen
- not everywhere correlated with the dense gas (green contours) distribution: strong γ-flux is expected from overlapping regions of CR and gas density
- strong indication of field aligned propagation
- various analyses of various sources (*e.g. Uchiyama et al 2012)* indicate that CR diffusivity is suppressed by up to a factor of ten

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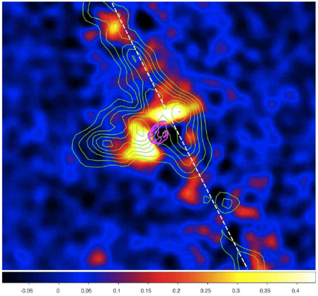

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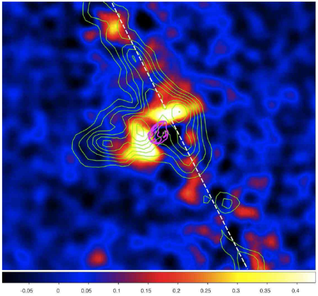

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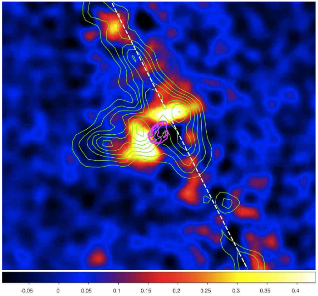

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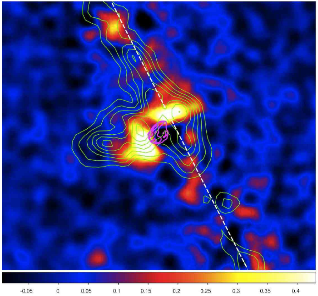

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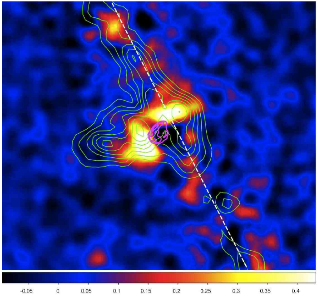

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Summary

- escape of CR from their acceleration site is treated **self-consistently with self-generated Alfven waves**
- resulting CR distribution is obtained in closed form
- strong **self-confinement** of escaping CR is demonstrated
- results are consistent with recent observations of W44 by *Fermi*-LAT
- escape spectra are roughly DSA-like power law, no signs of energy peaked escape

- Outlook
  - turbulence spreading across MF field likely to be important at lateral part of expanding CR cloud
  - CR pitch angle anisotropy must be strong at the edge of the cloud and needs to be included
  - combine escape with acceleration (ongoing work)

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