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Explaining low diffusivity and CR bubbles around SNRs

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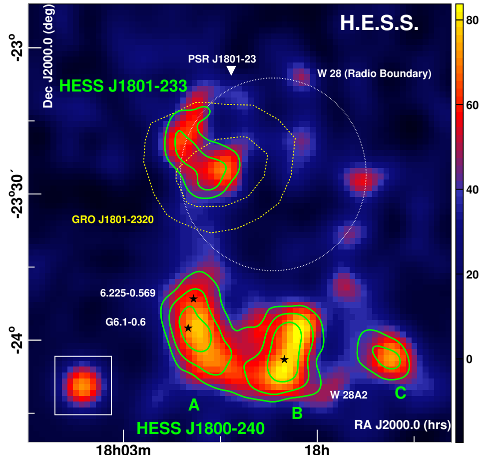
Outline

Introduction

Observation

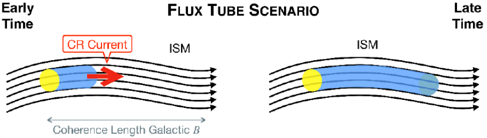
- Hints for strongly reduced diffusion coefficient observed near SNRs [Fujita et al. 2009; Gabici et al. 2010]



[Aharonian et al. 2008]

Source in the ISM

- interstellar magnetic field is coherent on scales of 10-50pc
- particles diffuse mainly parallel to magnetic field



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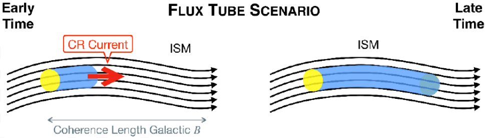

- $\Rightarrow$ On these scales particles fill a flux tube and the problem can be regarded 1D
- Flux given by: $\phi_{CR}(E > E_0) = n_{CR}(E > E_0)v_D = \frac{L_{CR}}{2\pi R_s^2 \Lambda E_0}$
- In this configuration CRs will excite a resonant streaming instability, hindering their escape
- Less efficient for high-energy particles [Nava et al. 2016, D'Angelo et al. 2016]

Formation of CR bubbles

Bell instability

Did we miss something?

Bell instability

Did we miss something? $\Rightarrow$ non-resonant streaming instability [Bell 2004]

- large growth rate γ_{max}
- on scale $k^{-1} \ll r_L \Rightarrow$ does not affect the CR current at first
- until saturation at $\sim 5 - 10\gamma_{max}^{-1}$, then cascades to larger scales

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- $$D = \frac{1}{3}\frac{vr_L}{P(k_{res})} \sim \frac{B_0^2}{\delta B^2}$$ $\rightarrow$ affects transport and enables strong particle scattering
- Condition:

$$\frac{\phi_{CR}(E > E_0)}{c} E_0 \gg \frac{B_0^2}{4\pi}$$

- This instability is often excited at SNR shocks

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Consequences

- Bell condition for SNR $\boxed{\dfrac{4\pi\phi_{CR}E_0}{cB_0^2} \approx 100}$, $\gamma_{max}^{-1} \approx 1.1(E/2.5\text{TeV})\,\text{yr}$
- Easy to see: Flux at SNR shock = flux of escaping particles, the condition holds at the shock $\Rightarrow$ it holds in the flux tube

[Schroer et al. 2021, ApJL]

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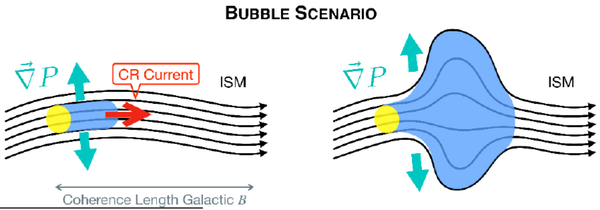
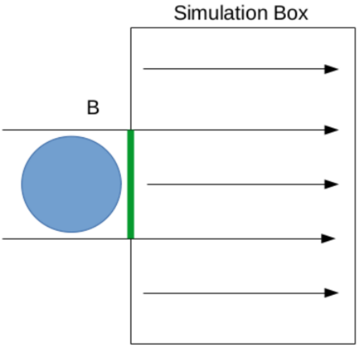
- mean free path $\lambda = \frac{3D}{v} \approx 1 \cdot E_{\mathrm{GeV}}^{1/2}\,\mathrm{pc} \Rightarrow$ high-energy CR escape ballistically
- Flux $\phi_{CR}(E > E_0) = n_{CR}(E > E_0)v_D$ conserved, but v_D decreases as particles start to transition to diffusive behavior
- $\Rightarrow P_{CR} \gg P_{gas} \rightarrow$ tube will expand in transverse direction, breaks 1D geometry



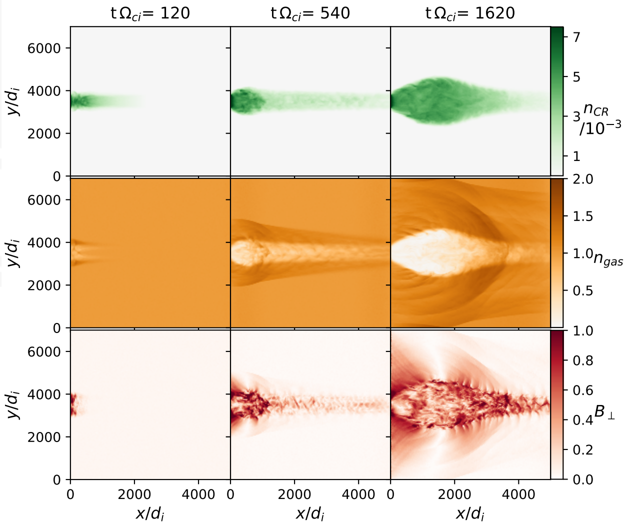
[Schroer et al. 2021, ApJL]

Hybrid PIC Simulation Setup

- Hybrid particle-in-cell simulation with dHybridR
- Solve Maxwell equations and equations of motion for macroparticles
- Electromagnetic fields due to moving particles



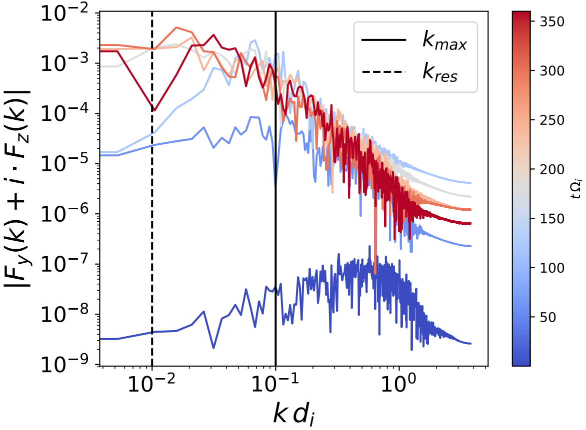
Evolution in 2D



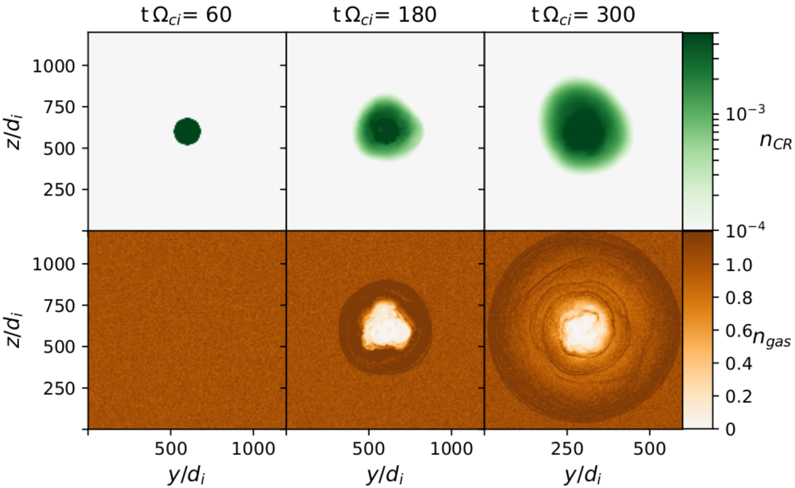
[Schroer et al. 2021, ApJL]

Power Spectrum

- Fastest growing mode around theoretical k_{max}
- Saturation, cascading to larger scales and formation of bubble all coincide with $\sim 10\gamma_{max}^{-1} \approx 100\Omega_{ci}^{-1}$



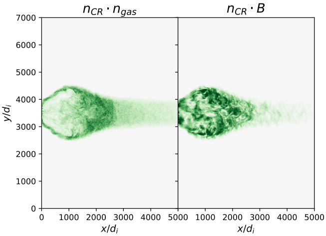
Evolution in 3D



[Schroer et al. PoS(ICRC2021)]

Implications

- Possible $\gamma-$ray morphology



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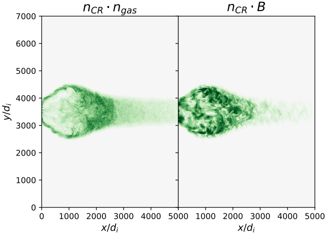

- Strong particle trapping influences the grammage accumulated by the particles
- Strongly dependent on achieved suppression of diffusion coefficient ξ and the gas density inside the bubble w.r.t. the ISM density η

$$\frac{X_{bubble}}{X_{Galactic}} \approx \frac{3 \times 10^{-1}\eta}{(\xi/10^{-2})} \left(\frac{L}{50pc}\right)^2$$

- $\Rightarrow$ With $\eta = 1$ and observed reduction of D this gives $\sim 10\%$

[Schroer et al. 2021, in preparation]

Conclusion

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new insights about escape of CRs from their sources:

- current of escaping particles generate a non-resonant instability which slows down their escape
- leads to formation of CR bubbles around sources with reduced diffusivity
- Important implications:
  - enhanced γ-ray emission from circumsource region
  - accumulated grammage of trapped CRs might be significant for secondary-to-primary ratios
  - electrons get trapped as well so that energy losses become important