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Galactic Cosmic Ray Transport around Sources

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Content

Introduction

Duality of CR Physics

- In order to understand CR phenomena we need to connect physics of individual particles on the small scales to observations on kpc scales
  - Treat CRs as charged particles and investigate fundamental interactions
  - Non-linear effect of charged particles streaming in a background plasma $\rightarrow$ generation of instabilities
  - Phenomenological approach motivated by observations
  - CR transport equation (Diffusion-advection equation on Galactic scales)
- E.g. diffusive behaviour on Galactic scales can be explained by turbulent magnetic fields due to particle streaming

Non-linear theory of CR escaping their sources

Magnetic instabilities

- Particle ensemble with high flux or strong spatial gradients $\Rightarrow$ magnetic instabilities
- Magnetic instabilities are solutions to the Vlasov and Maxwell equations: $B \sim e^{-\mathrm{i}\cdot\omega t}$ with $Im(\omega) < 0$
- Different kinds of instabilities:
  Resonant: grows on scales comparable to r_L
  Non-resonant: grows on scales much smaller than r_L

Bell instability

- very fast growing mode $\gamma_{max} \approx 0.1\,\mathrm{yr}^{-1}$
- 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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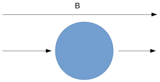
- $$D = \frac{1}{3}\frac{v r_L}{P(k_{\text{res}})} \sim \frac{B_0^2}{\delta B^2}$$ $\rightarrow$ affects transport and enables strong particle scattering
- happens in very short time compared to typical age of CR sources $\sim 10^{4..6}\,\text{yr}$
- Condition:

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

Source in the ISM

- interstellar magnetic field is coherent on scales of 10-50pc



- mean free path $\lambda = \frac{3D}{v} \approx 1 \cdot E_{\rm GeV}^{1/2}\,\mathrm{pc}$
- $\Rightarrow$ CR escape balistically on these scales $\Rightarrow$ 1D problem

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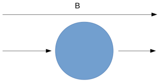

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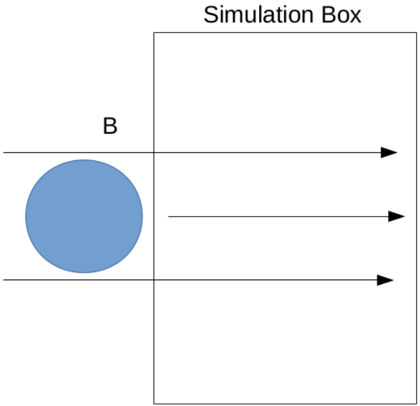
- $\Rightarrow$ CR escape balistically on these scales $\Rightarrow$ 1D problem
- flux given by:

$$\phi_{CR}(E > E_0) = \frac{L_{CR}}{2\pi R_s^2 \Lambda E_0}$$

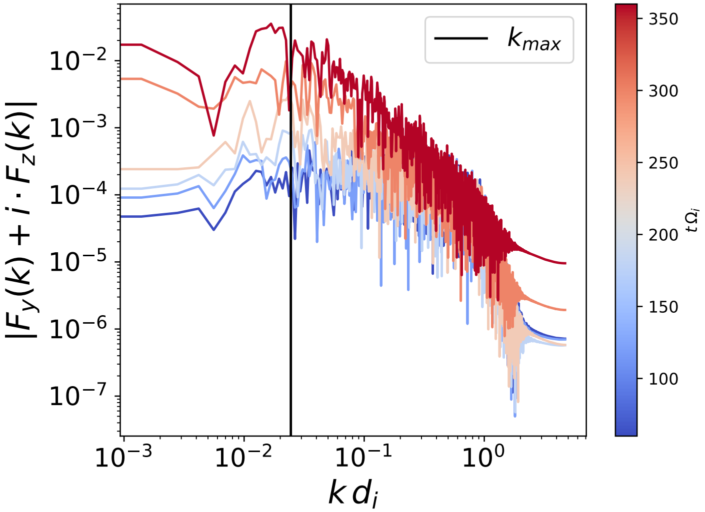
- Bell condition fulfilled: $$\frac{4\pi\phi_{CR}}{cB_0^2} \approx 5.2$$
- turns out satisfied for typical SNR and stellar clusters like Westerlund 1
- $\Rightarrow$ pressure in CR exceeds gas pressure $\rightarrow$ breaks 1D because overpressured region will expand in transverse direction

Simulation

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



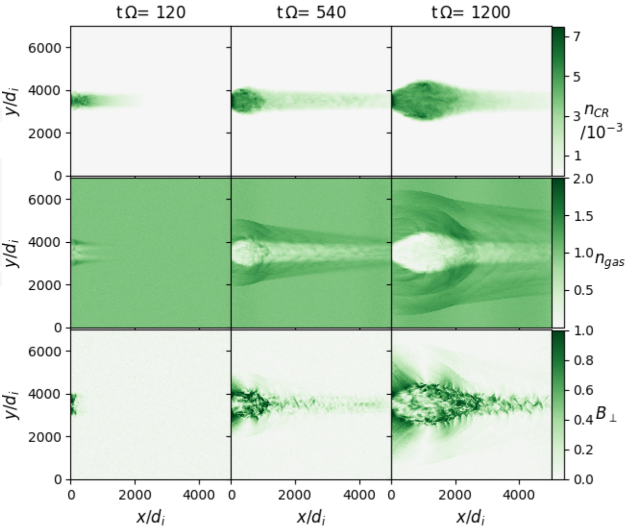
Bell mode



[1]

[1][Schroer et al. to be submitted to PRL]

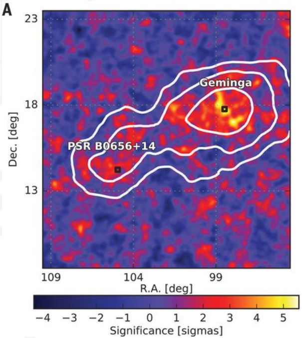
Evolution

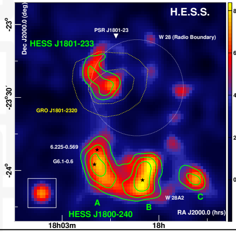


[2]

[2] [Schroer et al. to be submitted to PRL]

Observation





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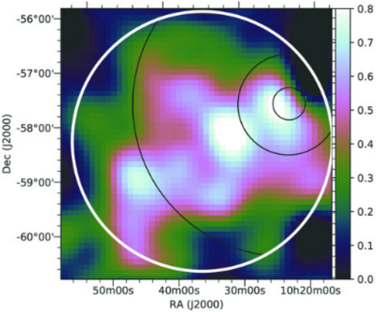


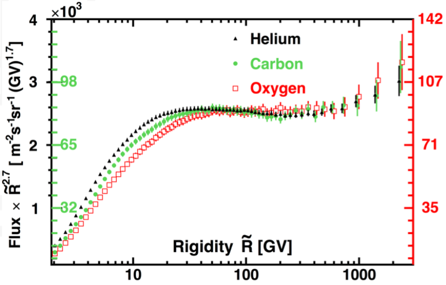
- Hints for strongly reduced diffusion coefficient observed near SNR, stellar clusters and pulsars

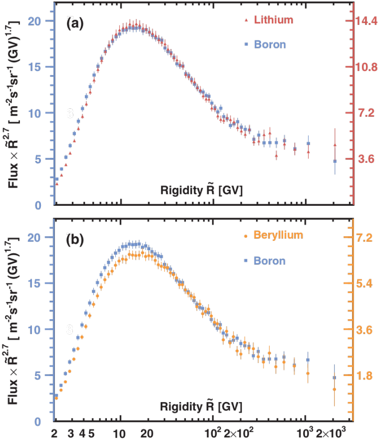
[3] [DOI: 10.1126/science.aan4880, 10.1051/0004-6361:20077765]

[4] [DOI: 10.1051/0004-6361/201732045]

Phenomenological Approach to CR transport in the Galaxy

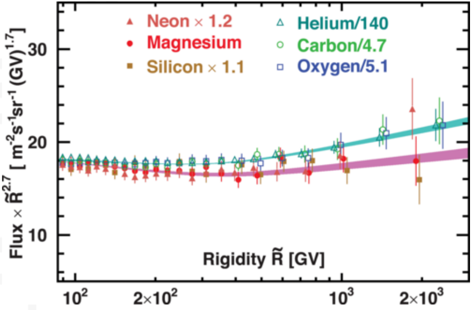
Observations





- High precision data of many different nuclei has lead to increasingly complete picture of CR transport
- Detected anomalies lead in the past to many new interesting challenges from a theoretical point of view like e.g. rising e^+/e^--ratio and the spectral break around 300 GV

Recent Observation

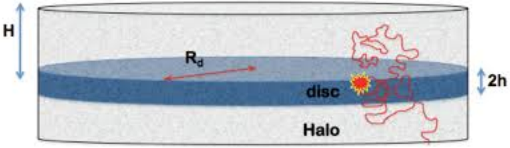


[5]

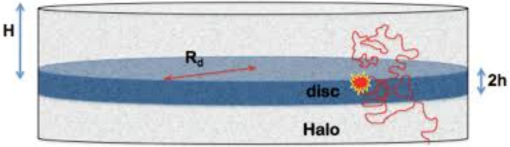
- All primaries, but have different slope
- Hint for new phenomenon like e.g. different sources or rather prediction by basic model?

[5][DOI: 10.1103/PhysRevLett.124.211102]

Standard Picture of CR Transport



$$-\frac{\partial}{\partial z}\left[D_a \frac{\partial f_a}{\partial z}\right] + v_A \frac{\partial f_a}{\partial z} - \frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p}$$
$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \left(\frac{dp}{dt}\right)_{a,\mathrm{ion}} f_a\right] + \frac{\mu v(p)\sigma_a}{m}\delta(z) f_a + \frac{f_a}{\hat{\tau}_{d,a}}$$
$$= 2h_d q_{0,a}(p)\delta(z) + \sum_{a'>a} \frac{\mu\, v(p)\sigma_{a'\to a}}{m}\delta(z) f_{a'} + \sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$



$$-\frac{\partial}{\partial z}\left[D_a\frac{\partial f_a}{\partial z}\right]+v_A\frac{\partial f_a}{\partial z}-\frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_a}{\partial p}$$

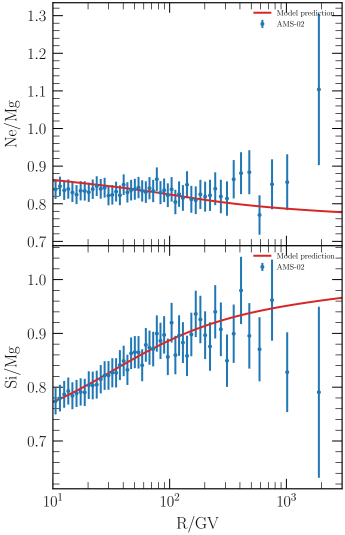
$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{a,\mathrm{ion}}f_a\right]+\frac{\mu v(p)\sigma_a}{m}\delta(z)f_a+\frac{f_a}{\hat{\tau}_{d,a}}$$

$$=2h_d q_{0,a}(p)\delta(z)+\sum_{a'>a}\frac{\mu\, v(p)\sigma_{a'\to a}}{m}\delta(z)f_{a'}+\sum_{a'>a}\frac{f_{a'}}{\hat{\tau}_{d,a'}}$$

$\sim$ 80 coupled differential equations

Biggest problem: Requires knowledge of all $\sigma_{a'\to a}$

Results



[6]

- Difference in slope is due to contribution from spallation rather than different injection slope
- Non trivial consistency check for underlying model that all spectra are reproduced with the same transport parameters which contain all the information about the microphysics

[6] [Schroer et al. to be submitted to PRD]

Conclusion and Outlook

Conclusion

new insights about escape of CR from their sources:

- CR generate instabilities which slow down their escape
- leads to formation of CR bubbles around sources which might be able to explain TeV halos

CR composition:

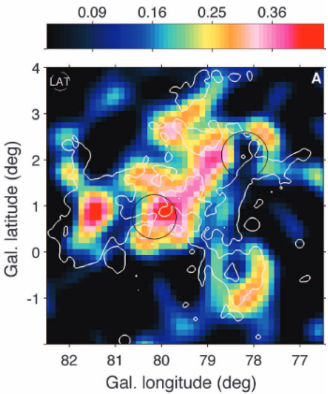
- able to reproduce flux of heavy elements with same injection spectrum
- main limitation given by cross section uncertainties

Outlook

- CR escape from their source modifies one of the pillars of CR theory
- $\Rightarrow$ many important implications and future projects:
  - use MHD code to follow bubble evolution for a longer time
  - electrons get trapped as well so that energy losses might become important $\rightarrow$ steeper spectrum
  - investigate possible γ-ray emission and accumulated grammage of trapped CRs
  - have a look at effect of source grammage on the fit of CR composition

Appendix

Observation



[7]

[7] [DOI: 10.1126/science.1210311]

CR basics

Vlasov equation:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = (\frac{\partial}{\partial t} + c\hat{p}\cdot\vec{\nabla}_r + (\frac{q}{p_0}\vec{p}\times\vec{B})\cdot\vec{\nabla}_p)f = 0$$

from this one can derive:

$$\frac{\partial}{\partial t}f + u\cdot\nabla f - \frac{1}{3}(\nabla\cdot u)p\frac{\partial f}{\partial p} = \nabla\cdot[D\cdot\nabla f] + q(p)$$

diffusion advection equation show 1/r solution in 3D:

$$G(x_0, t_0, x, t) = \frac{1}{\sqrt{4\pi D(t-t_0)}^3}e^{-\frac{(x-x_0)^2}{4D(t-t_0)}}$$

Solution in 3D with continuous injection:

$$n_{CR} = \frac{Q(p)}{4\pi Dr}$$

Standard picture of CR Transport

Rewrite as:

$$\Lambda_{1,\alpha}(E) I_\alpha(E) + \Lambda_{2,\alpha}(E) \partial_E I_\alpha(E) = Q_\alpha(E)$$

Solution:

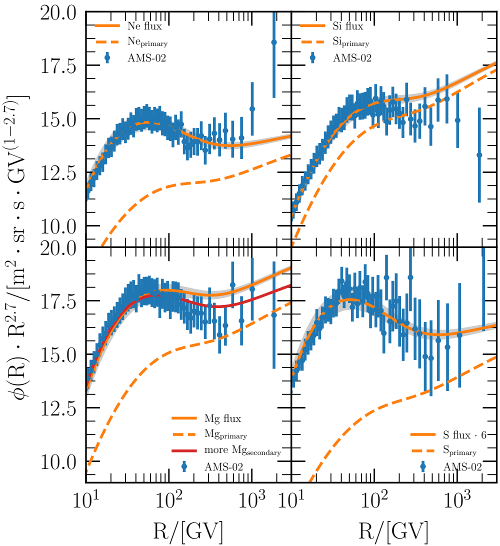
$$I_\alpha(E) = \int_E dE' \frac{Q_\alpha(E')}{|\Lambda_{2,\alpha}(E')|} \exp\left[-\int_E^{E'} dE'' \frac{\Lambda_{1,\alpha}(E'')}{|\Lambda_{2,\alpha}(E'')|} \right]$$

code solves iteratively this equation starting from heavy towards light elements

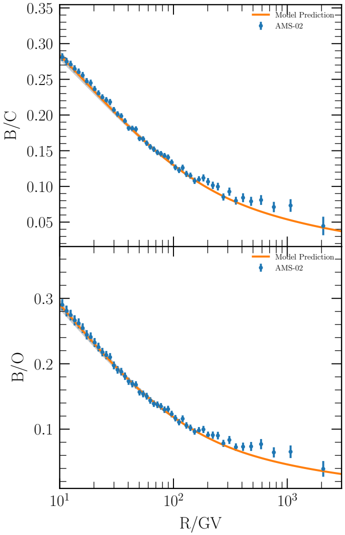
With the injection term:

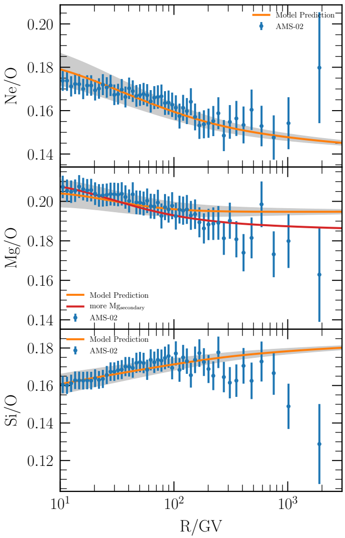
$$Q_\alpha(E) = \frac{A_\alpha p^2}{\mu v} \frac{\xi_\alpha E_{SN} \mathcal{R}_{SN}}{\pi R_d^2 \Gamma(\gamma) c (m_p c)^4} \left(\frac{p}{m_p c}\right)^{-\gamma} + \sum_{\alpha' > \alpha} \frac{I_\alpha(E)}{m} \sigma_{\alpha' \to \alpha} \quad (1)$$

Fit to heavy Nuclei



Fit to light Nuclei





3D Simulation