Propagation of Low-Energy Cosmic Rays in Molecular Clouds

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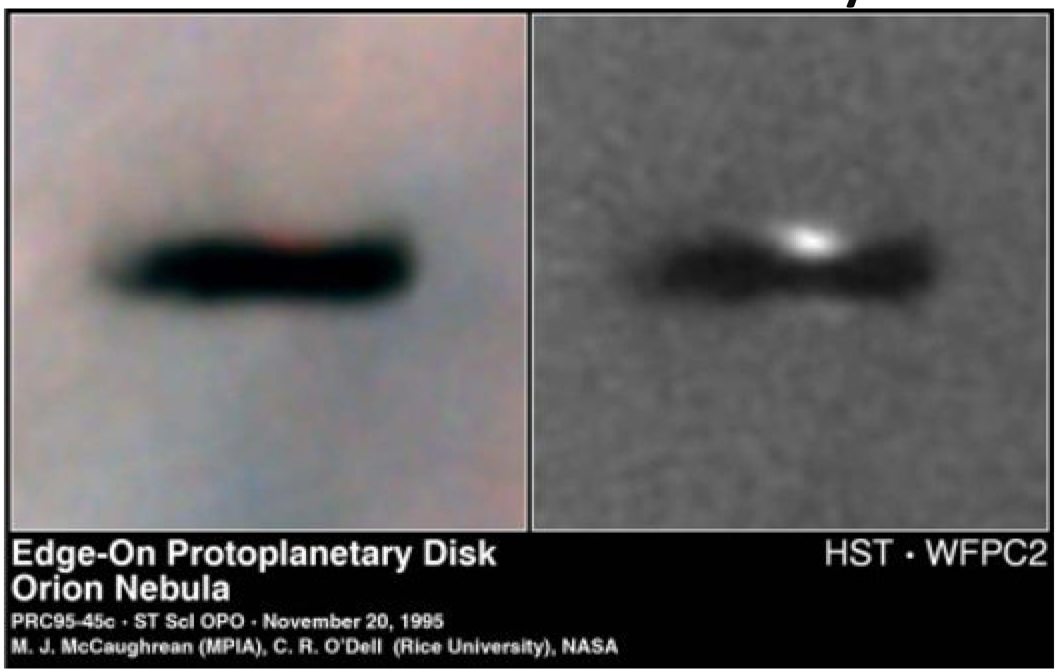

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Low Energy Cosmic Rays

- The cosmic ray ionization rate is a per second ionization rate from protons

  ζ_H: H + CRP -> H^+ + e^- + CRP

  ζ_{H2}: H_2 + CRP -> H_2^+ + e^- + CRP

$$\zeta_H(N_H) = 1.8 \times \frac{5}{3} \times \int_0^\infty 4\pi\sigma_{i,\mathrm{H}}(E) j_{\mathrm{IC}}(E, N_H) dE$$

σ goes as 1/E for low energies.

Low energy cosmic rays (< few hundred MeV) dominate the ionization rate.

Low energy cosmic rays are shielded from direct observation by the solar wind.

ζ has been assigned values ranging from 10^{-18} – 10^{-14} s^{-1}

Distribution Function, Number Density, and Flux of Cosmic Rays

- The distribution function for cosmic rays is:

$$f(\mathbf{x}, \mathbf{p}, t)$$

- The number density is:

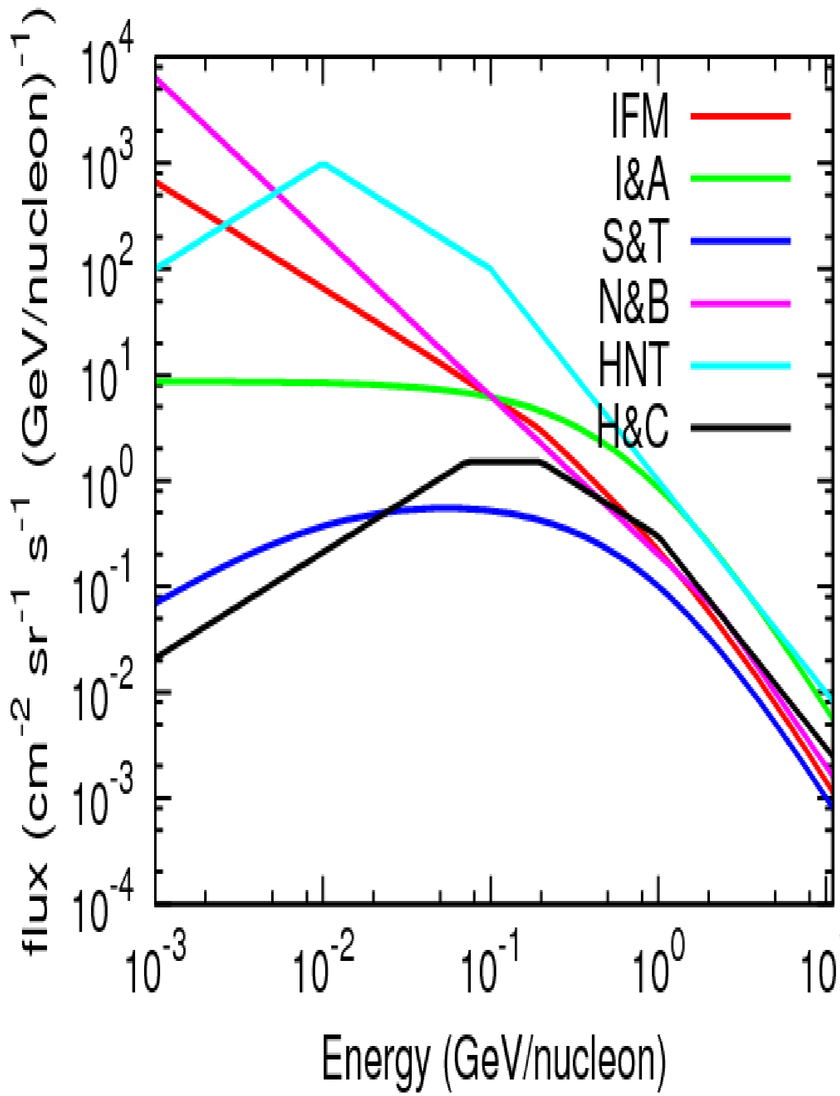
$$n = \int f(\mathbf{x}, \mathbf{p}, t) d\mathbf{p}$$

- The flux can be related via:

$$\Phi \ (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}) = \int \mathbf{p} \cdot \hat{\mathbf{n}} f(\mathbf{x}, \mathbf{p}, t) d\mathbf{p}$$

Initial Cosmic Ray Flux for low-energy Cosmic Rays

- There are many flux-spectra below ~1GeV to choose from, because the spectrum cannot be directly observed.
- We use the highest cosmic ray flux for this model.
- We treat only protons in this model.
- Electrons are simple to add.
- We apply a low energy cutoff to the protons at 1 MeV



A Reasonable Approximation

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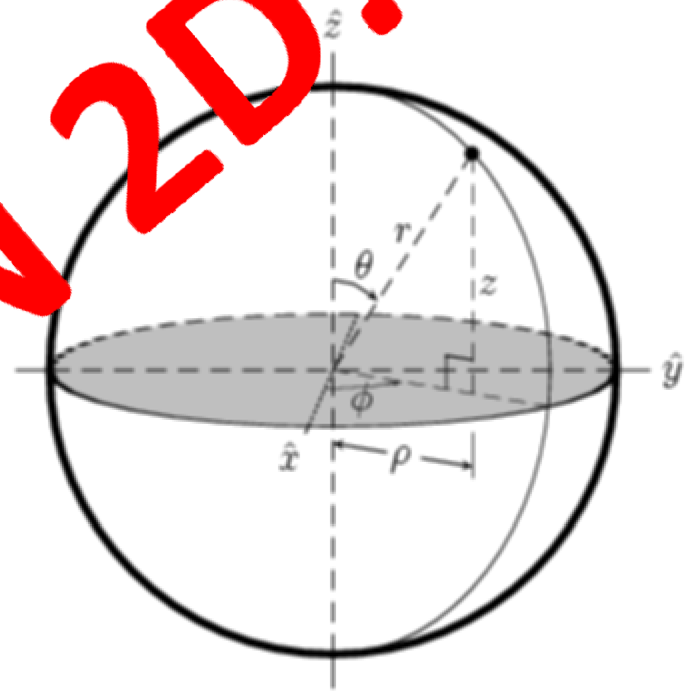


NOW IN 2D!

The Boltzmann Transport Equation

- We use the Vlasov equation with a collisional term:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + q(\mathbf{v} \times \mathbf{B} + \mathbf{E}) \frac{\partial f}{\partial \mathbf{p}} = \left. \frac{\partial f}{\partial t} \right|_{coll}$$

- The collision term is difficult to determine in this form.
- The Fokker-Planck Equation is a covenient approximation (see R.F. Pawula(1967)).
- We use the Fokker-Planck Equation in the form used by Cesarsky & Volk(1978).

The Magnetic Field

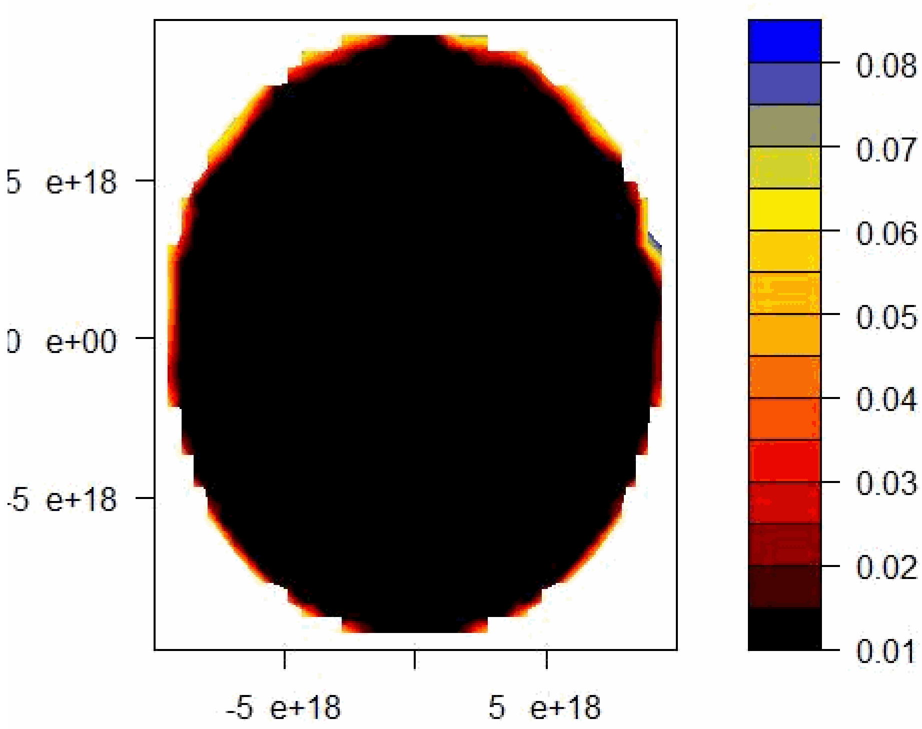
- The density outside the cloud is set at 10 cm^{-3}.
- The density inside the cloud is set at 10^4 cm^{-3}.
- The ambient magnetic field outside the cloud is set to 1 μG.
- The magnetic field increases as $\rho^{1/2}$
- The cloud and medium is treated as having an ionization fraction of $x(e^-) = 10^{-4}$
- As such, the bulk density does not move with the magnetic fields.

Solving the Boltzmann Transport Equation: Two Examples

- We solve the Transport Equation using the Crank-Nicholson method.
- At each step in time, we place the number density of the cosmic rays into the ZEUS code, and evolve it within the set conditions, to determine the magnetic field fluctuations.
- We then apply the new magnetic field to the Transport Equation, and repeat.
- Results are shown for 10 MeV and 1 GeV protons streaming through a cloud.

Video of the Solution in terms of the Number Density

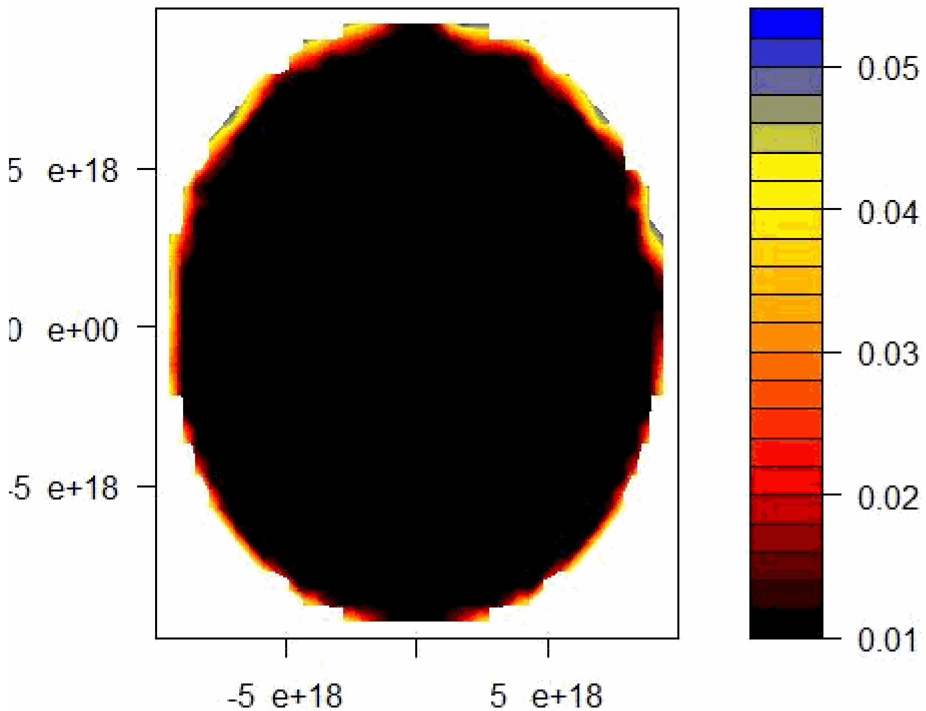
- 10 MeV Case:



The color scheme is arbitrary.

Video of the Solution in terms of the Number Density

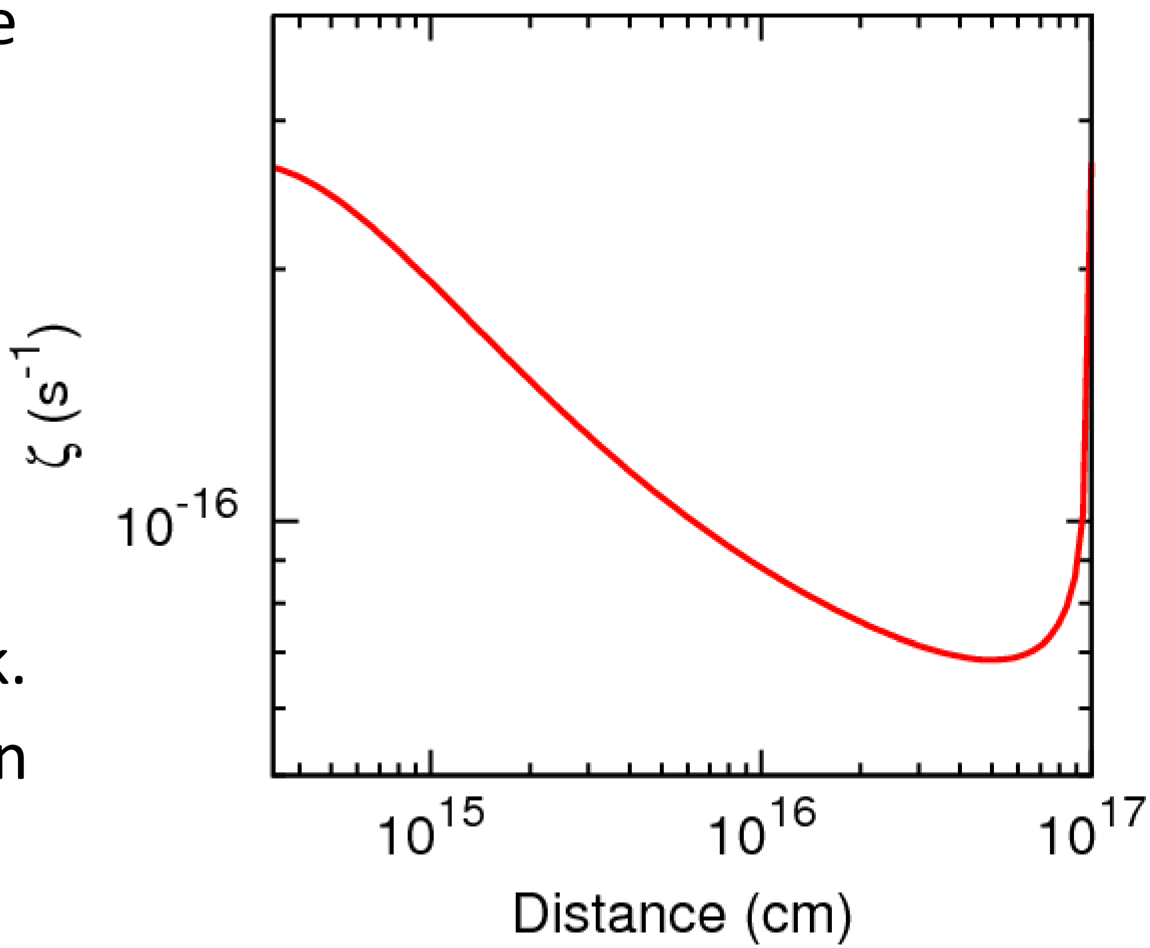
- 1 GeV case:



The color scheme is arbitrary.

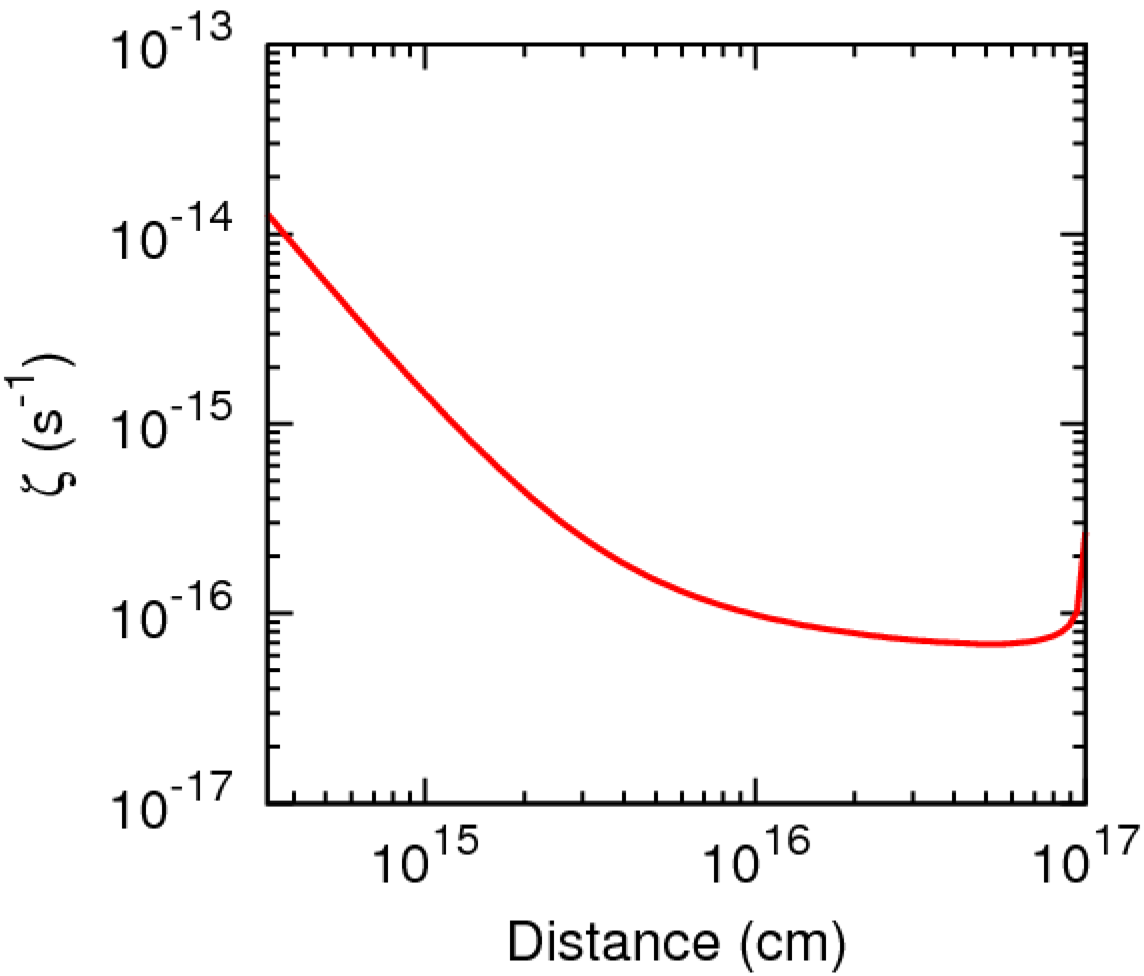
The average $\zeta(N_H)$ for a cloud with an isotropic flux

- We find the average flux $j_{av}(E)$ through a ``sightline'' of the sphere.
- We integrate to determine the ionization rate, as per the first equation in this talk.
- Here we consider an isotropic flux.



The average $\zeta(N_H)$ for a cloud with a strong flux impinging on one side

- Here we consider a non-isotropic flux.
- A strong j(E) of cosmic rays is impinging on one side of the cloud, with a low-energy cutoff of 100 eV.



Future Work

- Check the code, making sure each factor is correct.
- Test the code with different fluxes.
- Test the code with various initial density distributions.
- Compare results to models using different magnetic field effects, mentioned in Cesarsky & Volk, applied by Padovani+2011,Rimmer+2011, to find out which effects mentioned, if any, are significant.
- Develop analytical fits for the ionization rate.
- Use these fits in a subroutine for both standard and disc chemical models to calculate zeta at any given point, given an impinging cosmic ray flux, ambient B-field, etc.

Acknowledgements

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