Cosmic Rays & Magnetic Fields

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Why are Cosmic Rays Important?

- Source of ionization & heating
- Dynamical support
- Drive winds
- Joint cosmic ray acceleration & magnetic field amplification
- Window on early history of magnetic fields

The Plan of This Talk

- Scope of the problem
- Review of interaction between cosmic rays & ISM
- Illustrative model for a Galactic wind (*w. John Everett*)
- Cosmic ray-ISM interactions if field is weak or flux is high
- Final questions

The Evidence

- Light elements (Li, Be, B) in atmospheres of oldest Galactic Halo stars widely interpreted as spallation products.
  - At low metallicity, abundance scales linearly with Fe abundance.
  - Explained by CNO nuclei accelerated to hundreds of MeV reacting with ambient ISM material that formed these stars.
- Cosmic ray acceleration & confinement demands *some* magnetic field (EZ2003)
- The highest z evidence for magnetic fields outside of AGN

Ionization & Heating

- Primarily by ions at a few MeV/nucleon
- Approximately SN ejection energy ($v \sim 1.4 \times 10^9 E_{MeV}^{1/2}$cm/s)
- Column density for energy loss:

$$N_c \equiv \frac{vEn(H)}{\dot{E}} \approx 8.8 \times 10^{20} E_{Mev}^2 \left(1 + 0.46 \log E_{MeV}\right) \mathrm{cm}^{-2}.$$

Low energy protons need not be magnetically accelerated & are naturally smothered, not magnetically confined.

Review of Acceleration Theory

- Acceleration in shocks by the first order Fermi process: trapped in converging preshock + postshock flow by magnetic fluctuations which scatter them.
- Alfvenic fluctuations are amplified by cosmic ray streaming anisotropy; unstable if $v_D > v_A$.
- Acceleration efficiency determined by feedback of cosmic rays on shock, including growth of fluctuations.

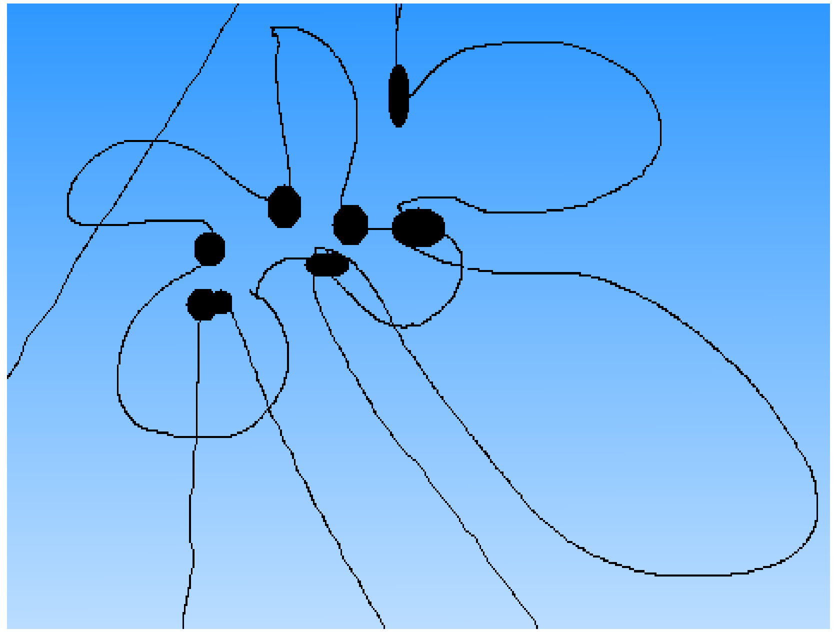
Review of Propagation Theory

- Diffusive propagation by scattering from r_c scale fluctuations
- $D_{||} \sim c^2/[3\omega_c(\delta B/B)^2]$
- Little cross-field diffusion: magnetic fieldlines must wander out of the Galaxy.
- Streaming instability aids self-confinement
- Anisotropic Alfvén wave cascade impedes confinement.

Global Equilibrium. I

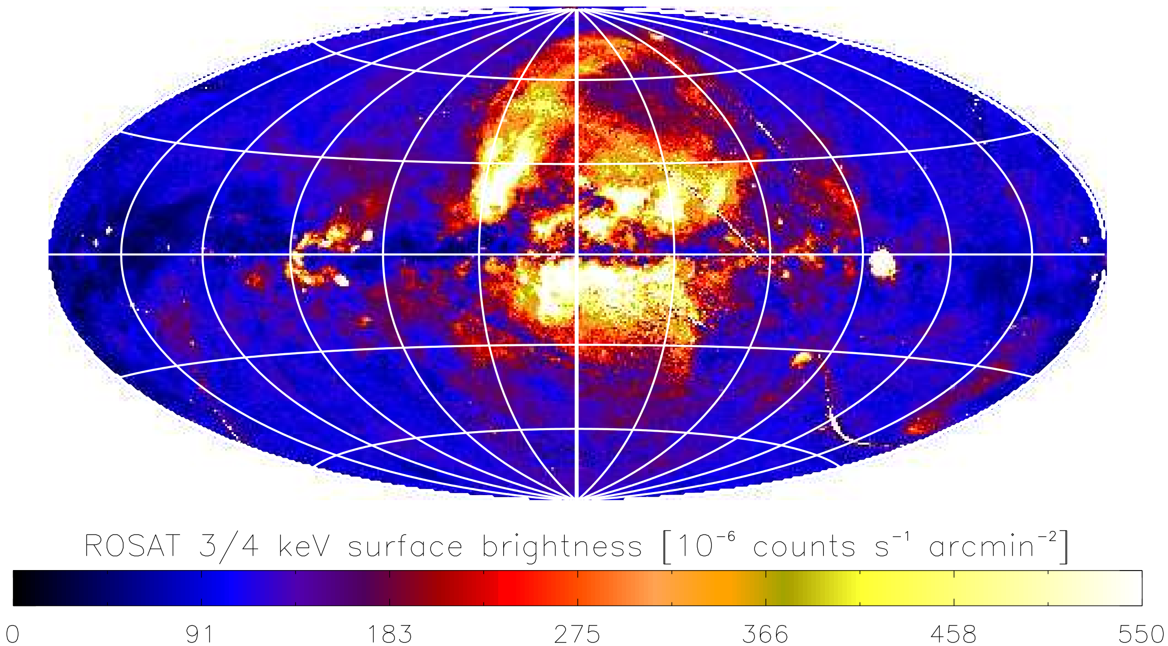
- **Q.** What is the minimum $\frac{B^2}{8\pi}$ for cosmic ray confinement in a galactic potential?
- **A1.** A horizontally uniform, plane stratified equilibrium is possible for *any* $\frac{B^2}{8\pi P_{cr}}$ as long as $r_c/H < 1$ & the cosmic rays are well scattered.
- **A2.** If all the mass is in clouds...

Global Equilibrium. II



It can be shown from the virial theorem that $\frac{B^2}{8\pi P_{cr}}$ must be ≥ 1 to confine the cosmic rays.

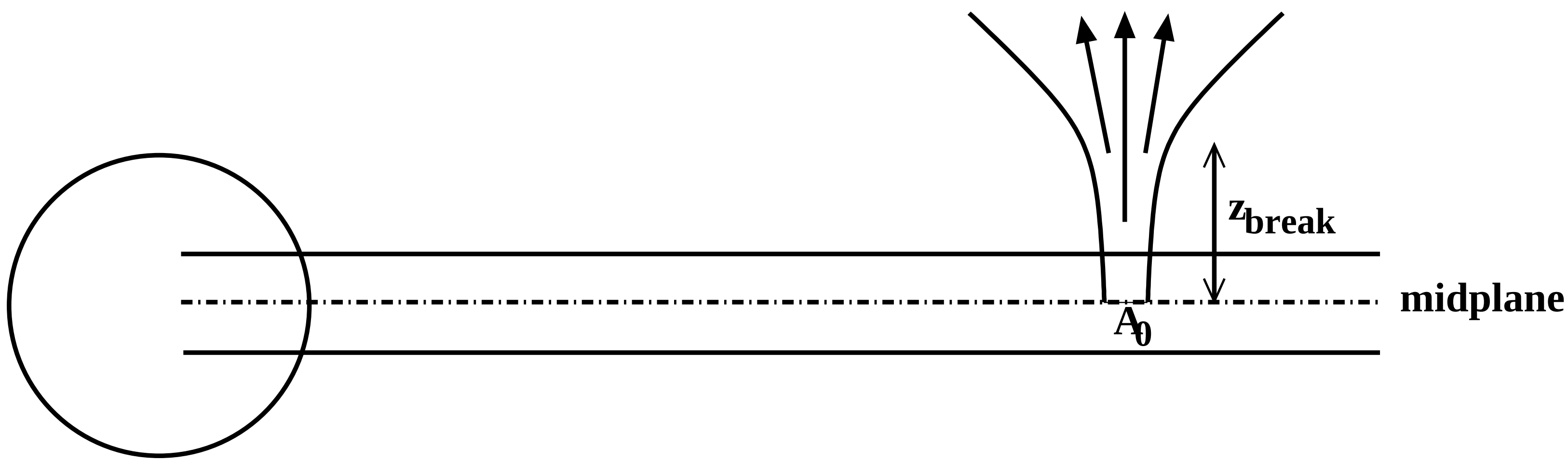
A Wind From the Milky Way?



ROSAT 0.75 keV image of the inner Galaxy, (Snowden et al. 1997) reproduced in Everett et al. 2007. We found that the x-ray bulge in the southern hemisphere can be fit with a combined thermal & cosmic ray driven wind.

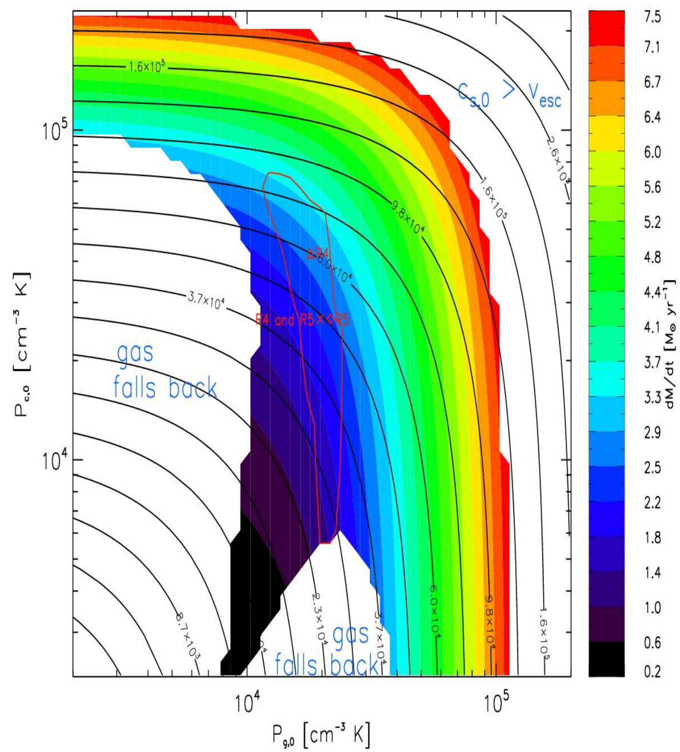
Wind Properties

- Based on fluid treatment of cosmic rays using winds eqns. given by Breitschwerdt et al. 1991
- Constrained by known ISM parameters within 1.5-4.5 kpc



Flared flux tube geometry replicated in an annulus.

Results of Parameter Study



Winds in the (P_g, P_{cr}) space. Colors indicate mass loss rates.

The best fits to the R4 and R5 Rosat bands are indicated.

The contour is $\chi^2 = 2\chi^2_{min}$.

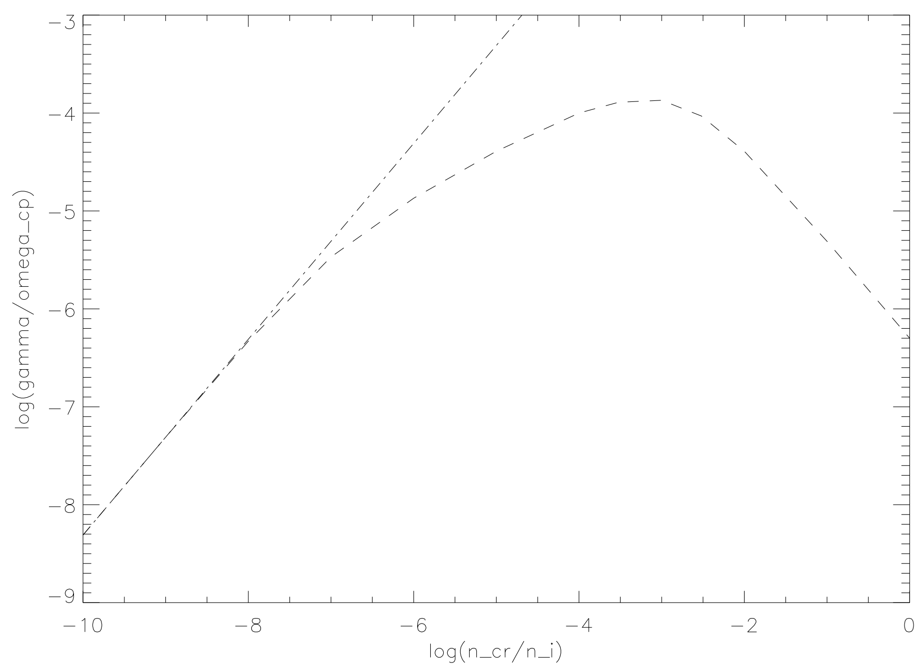
High Fluxes, Weak Fields

- Streaming instability is modified when

$$\frac{8\pi P_{cr}}{B^2}\frac{v_D}{c} \geq 1.$$

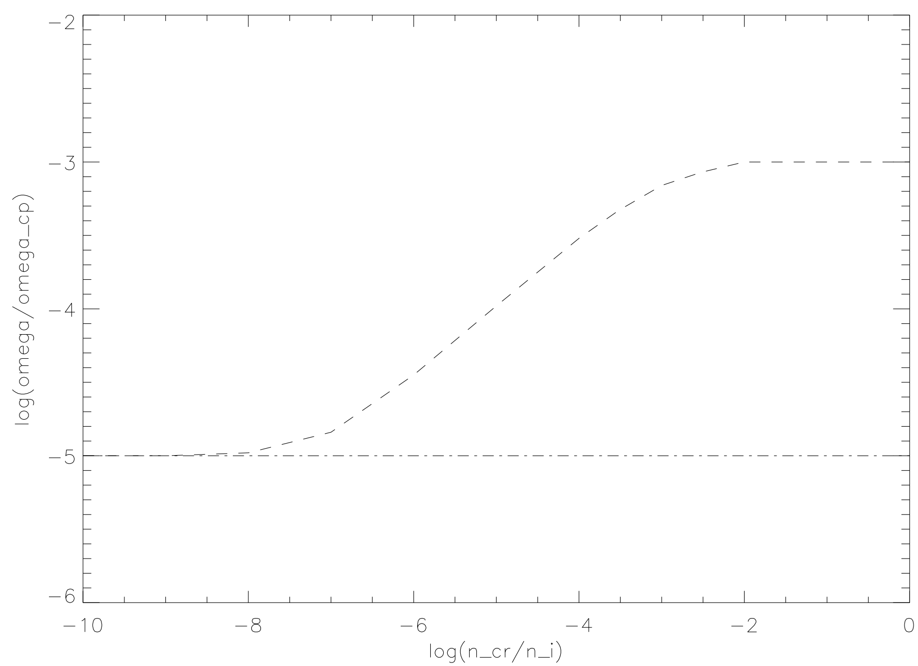
- In the Milky Way this now only occurs in supernova shocks.
- Would occur in young galaxies with $B \leq 10^{-9}G$

Instability Growth Rate



Growthrate of the cosmic ray streaming instability as $\frac{n_{cr}}{n_i}$ is increased. The dashed line is the result from Z2003, the dot-dashed line is the extrapolation of the low flux result. In this case, $\beta_A = 10^{-5}$ and $\beta_D = 10^{-3}$.

Wave Frequency



Real part of the wave frequency ω_r for cosmic ray modified waves, with the same parameters as the previous slide. At large cosmic ray densities, the wave speed approaches v_D instead of v_A.

Force on the Gas

- Streaming cosmic rays transfer momentum to the waves
- In a steady state, this momentum is transferred to the gas
- Resulting force parallel to $\mathbf{B}$ is $-\nabla_{\|} P_{cr}$. Also

$$\nabla_{\|} P_{cr} = -\gamma \frac{|\delta B|^2}{2\pi v_A} \left(\frac{\omega_r}{k v_A} \right).$$

- The force reduces to $\rho_{cr} \nu (v_D - v_A)$ under standard conditions but is bigger for high cosmic ray fluxes.

Heating the Gas

- Cosmic ray energy is transferred to the waves and thence to the background. This heats the gas.
- Heating rate:

$$\dot{\mathcal{E}}_{cr} = \frac{1}{2}\frac{kv_A}{\omega_r}\left(1 + \frac{|\omega|^2}{k^2 v_A^2}\right) v_A \nabla_{\|} P_{cr}.$$

- This reduces to $v_A \nabla_{\|} P_{cr}$ under standard conditions but is larger at high cosmic ray fluxes.

Final Questions

- Are cosmic rays an important ingredient in mass loss from young galaxies?
  - Likely significant in the inner Milky Way.
  - Exert a large force & deposit significant heat.
- Are cosmic rays an important ingredient in magnetic field evolution?
  - Streaming instability amplifies the field on small scales
  - A source of helical magnetic turbulence
- What was the flux of low energy cosmic rays?
- What are the constraints on the cosmic ray population from the γ ray background?