Cosmic Rays Help Drive Galactic Winds

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Talk Conclusions

Three main sections/points to this talk:

- Cosmic rays can transfer both momentum and energy to gas via magnetic fields (we call this the “Streaming Instability”).

- Cosmic rays can substantially help launch galactic winds. A Galactic wind model successfully fits X-ray and synchrotron emission observed towards the center of the Galaxy.

- Early calculations predict that cosmic-ray pressure does not change in diffuse clouds: clouds are not driven by cosmic-ray pressure, and are not biased tracers of cosmic-ray density.
Motivating Observations

- Multi-component Halos: NGC 4631
- ROSAT: 0.75 keV emission

Cosmic-Ray Pressure

Wind Model vs. Multiwavelength Galactic Data

Cosmic Rays and Cloud Driving?

Conclusions
Cosmic rays and magnetic fields in the halo of a spiral galaxy.
From Snowden et al. (1997):

Soft X-ray emission in the halo of our Galaxy?
Cosmic-Ray Pressure

Motivating Observations

Cosmic-Ray Pressure

- Interaction via the Streaming Instability
- Cosmic-Ray Hydrodynamics

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Conclusions
If \( \nabla P_{\text{cr}} \neq 0 \) and \( v_{\text{CR}} > v_{\text{Alfven}} \), with a \( \mathbf{B} \) field:

- As CRs stream along magnetic field lines, on gyro-orbits, they interact with Alfvén waves with \( \lambda \sim r_{\text{gyro}} \).
- The CRs are scattered in pitch angle by the \( \delta \mathbf{B} \) perturbation, donating momentum to the waves; the waves grow.

\[
\nu \sim \frac{\pi}{4} \omega_{\text{CR}} \left( \frac{\delta \mathbf{B}}{\mathbf{B}} \right)^2
\]

Cosmic Ray proton
Cosmic-Ray Hydrodynamics

Assuming a steady-state system, acted only upon by gravity, and for $\nabla P_{cr}$ parallel to $B$:

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

$$\nabla \cdot [\rho \mathbf{v} : \mathbf{v} + P_g \mathbf{l} + P_w + P_{cr}] = -\rho \nabla \Phi$$

$$\nabla \cdot \left( \left[ \frac{1}{2} \rho \mathbf{v}^2 + \frac{\gamma_g}{\gamma_g - 1} P_g + \rho \Phi \right] \mathbf{v} + P_w \mathbf{v} + \frac{1}{\gamma_{cr} - 1} \left[ \gamma_{cr} (\mathbf{v} + \mathbf{v}_{Alfven}) P_{cr} - \kappa \frac{\partial P_{cr}}{\partial z} \right] \right) = 0$$

And for the CRs and waves:

$$\nabla \cdot \left( \frac{\gamma_{cr} (\mathbf{v} + \mathbf{v}_{Alfven}) P_{cr} - \kappa \nabla P_{cr}}{\gamma_{cr} - 1} \right) = (\mathbf{v} + \mathbf{v}_{Alfven}) \cdot \nabla P_{cr}$$

$$\nabla \cdot \left( E_w (\mathbf{v} + \mathbf{v}_{Alfven}) + P_w \mathbf{v} \right) = \mathbf{v} \cdot \nabla P_w - \mathbf{v}_{Alfven} \cdot \nabla P_{cr}$$

These equations can be used to derive a hybrid, cosmic-ray and thermal-pressure driven outflow. [See e.g., McKenzie & Webb (1984), Breitschwerdt et al. (1991), and Kulsrud (2005)].
Wind Model vs. Multiwavelength Galactic Data

Motivating Observations

Cosmic-Ray Pressure

Wind Model vs. Multiwavelength Galactic Data
- ROSAT: 0.75 keV emission
- Fitting the 0.85 keV X-ray Emission
- Fitting the Synchrotron Emission
- New: Predictions for Fermi Observations
- New: Adding Rotation & Magnetic Driving
- Cosmic Rays Help Drive Winds

Conclusions
ROSAT: 0.75 keV emission

From Snowden et al. (1997):

Thermal emission over latitude $\lesssim 17^\circ$ and longitude $\lesssim 30^\circ$, especially visible in southern hemisphere of the Galaxy.
Fitting the 0.85 keV X-ray Emission

Wind model demonstrably better at 0.85 keV ($\sim 2$ lower in $\chi^2$).
Fitting the Synchrotron Emission

Fits synchrotron emission at high latitudes.
New: Predictions for Fermi Observations

Motivating Observations

Cosmic-Ray Pressure

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Gamma-Ray “Bubble” seen at similar scales in Fermi data already? (Su, Slater & Finkbeiner, arXiv:1005.5480)
New: Adding Rotation & Magnetic Driving

We are also improving the model in several ways:

- Moving from 1D to 2.5D
- Adding in Galactic rotation (centrifugal driving)
- Toroidal magnetic fields included (driving via magnetic pressure)
- Similar to the work of Zirakashvili et al. (1996), but in a general-purpose semi-analytic model.
Cosmic rays allow winds for a wider range of gas pressures. *NB:* Impact of cosmic-ray pressure scales with $B$. 
Cosmic Rays and Cloud Driving?

- Setting Up a Simple Diffuse Cloud
- Cosmic-Ray Pressure is Constant in Clouds

Conclusions
Setting Up a Simple Diffuse Cloud

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Does cosmic-ray pressure have an effect on cool clouds in winds?

(Simple cloud model for cosmic rays to be injected into.)
Constant cosmic-ray pressure implies no cloud driving.
Conclusions
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References:
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## Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Fixed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$ [Galactocentric]</td>
<td>3.5 kpc to 4.5 kpc</td>
<td>Fixed</td>
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<tr>
<td>$P_{\text{cosmic ray},0}/k_B$</td>
<td>$2.2 \times 10^4$ K cm$^{-3}$</td>
<td>Fixed</td>
</tr>
<tr>
<td>$B_0$</td>
<td>5.2 $\mu$G</td>
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<tr>
<td>$\alpha$</td>
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<td>Fixed</td>
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<tr>
<td>$P_{\text{thermal},0}/k_B$</td>
<td>$4.0 \times 10^4$ K cm$^{-3}$</td>
<td>Varied</td>
</tr>
<tr>
<td>$n_0$</td>
<td>$8.8 \times 10^{-3}$ cm$^{-3}$</td>
<td>Varied</td>
</tr>
<tr>
<td>$z_{\text{break}}$</td>
<td>4.0 kpc</td>
<td>Varied</td>
</tr>
</tbody>
</table>

**NB**: These parameters are close to those inferred at $R = 3.5$ kpc.

**Model Outputs:**

\[
\begin{align*}
v_\infty &= 580 \text{ km s}^{-1} \\
\dot{M} &= 2.2 \ M_\odot \ \text{yr}^{-1}
\end{align*}
\]
How unique is this fit?

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