Cosmic Rays: Agents of Feedback, Probes of Star Formation

Ellen Zweibel

zweibel@astro.wisc.edu

Departments of Astronomy & Physics

University of Wisconsin, Madison

and

Center for Magnetic Self-Organization

in

Laboratory and Astrophysical Plasmas

Outline

- The basis for cosmic ray hydrodynamics
  - Observational motivation
  - Self confinement picture
  - Extrinsic turbulence picture
  - Effects of magnetic field & background gas properties
- Application to galactic winds
- Cosmic rays as a probe of star formation

Salient Observations

- Proken power law spectrum; $E^{-2.6}$ in GeV range; $\langle E \rangle \sim 3$GeV.
- Energy density $U_{cr} \sim U_B \sim U_{th} \sim$ 1 eV cm^{-3}.
- Isotropic to 0.1 - 0.01%.
- Confined for $\sim$ 2 10^7 yr & cross 3-5 gm cm^{-2}.
- Composition is similar to interstellar (*not r-process*).
- Occupy a thick disk, similar to warm ionized gas.
- Robust Far-IR radio correlation for many galaxies.

Diffusive Transport

- Well defined B field that varies little over a gyro-orbit $r_g \sim 0.2(E_{GeV}/B_\mu)$AU.
- Slow drifts: $v_d/v \sim r_g/L_B \ll 1 \rightarrow$ particles tied to fieldlines.
- Cosmic rays diffuse up & down the fieldlines, & the fieldlines wander (FLRW).

$$D \sim \frac{c}{3}\frac{\lambda_c \lambda_B}{\lambda_c + \lambda_B}$$

- $\lambda \sim 1$pc in Milky Way; $D \sim 10^{28-29}$ cm^{2}s^{-1}.

Gyroresonant Pitch Angle Scattering

For fluctuations of frequency ω & parallel wavenumber k,

$$\omega - kv\mu \pm n\omega_c = 0,$$

where $\mu \equiv \mathbf{v} \cdot \mathbf{B}/vB$ & $n = \pm 1$ is the strongest resonance. Summing over many uncorrelated scatterings, the mean scattering rate ν is

$$\nu = \frac{\pi}{4}\omega_c k_r \frac{\delta B_k^2}{B^2}.$$

Fokker-Planck Equation

For $\omega_c^{-1} \ll \nu^{-1} \ll \tau_{dyn}$, a Fokker-Planck eqn. for the gyor-averaged distribution function holds

$$\frac{\partial f}{\partial t} + \mu v \hat{\mathbf{n}} \cdot \nabla f = \frac{df}{dt}|_{coll};$$

$$\frac{df}{dt}|_{coll} = \sum_{\pm} \frac{\partial}{\partial \mu} \left[\frac{1-\mu^2}{2} \nu_{\pm} \frac{\partial f}{\partial \mu} + \nu_{\pm} \hat{\mathbf{n}} \cdot \mathbf{w}_{\pm} m \gamma \frac{\partial f}{\partial p} \right],$$

with $\pm \equiv$ direction of wave propagation & $\mathbf{w}_{\pm} \equiv \mathbf{v} \pm \mathbf{v}_{\mathbf{w}}$.

Momentum Transfer

Multiply Fokker-Planck eqn. by $p\mu$ & integrate over momentum space.

$$\frac{\partial}{\partial t}(n_c p_D) = -\nabla_{\|} P_c - n_{cr}\nu(v_D - v_w).$$

- Scattering drives f toward isotropy in the frame of the waves
- In a steady state, acceleration down the pressure gradient balances friction.
- Waves propagating in both directions contribute to ν

Energy Transfer: I

Work with the μ averaged Fokker-Planck eqn. for F

$$\frac{\partial F}{\partial t} + \frac{1}{3p^2}\frac{\partial}{\partial p}(p^3\mathbf{u}\cdot\nabla F - (\nabla\cdot\mathbf{u})\frac{p}{3}\frac{\partial F}{\partial p} = \frac{dF}{dt}|_{coll};$$

$$\frac{dF}{dt}|_{coll} = \nabla_{\|}D_{\|}\nabla_{\|}F + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\right)\frac{\partial F}{\partial p},$$

where $\mathbf{u} \equiv \mathbf{v} + \langle\frac{3}{2}(1-\mu^2)\frac{\nu_+\mathbf{w}_+ - \nu_-\mathbf{w}_-}{\nu_+ + \nu_-}\rangle$, $D_{\|} \equiv v^2\langle\frac{1-\mu^2}{2(\nu_+ + \nu_-}\rangle$,
$D_{pp} \equiv 4m^2\gamma^2 w^2\langle\frac{1-\mu^2}{2}\frac{\nu_+\nu_-}{\nu_+ + \nu_-}\rangle$.

- u is a mean (fluid plus wave) velocity.
- D_{pp} represents 2nd order Fermi acceleration & requires waves traveling in both directions.

Energy Transfer: II

Multiply by particle energy $\epsilon \sim cp$ & integrate over momentum space. Ignoring Fermi term for now,

$$\frac{\partial U_c}{\partial t} + \mathbf{u} \cdot \nabla U_c = -\frac{4}{3} U_c \nabla \cdot \mathbf{u} + \nabla \cdot \kappa_{\mathbf{c}} \cdot \nabla U_c$$

as we'd expect for a relativistic, diffusive gas with velocity $\mathbf{u} = \mathbf{v} + \mathbf{v_w}$.

Energy Transfer: III

Combine with the ideal fluid equations to yield an energy transport equation

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \frac{P_g}{\gamma_g - 1} + \frac{P_c}{\gamma_c - 1}\right) = -\nabla \cdot \mathbf{F} + Q;$$

$$\mathbf{F} = \mathbf{v}\left(\frac{1}{2}\rho v^2 + \frac{\gamma_g P_g}{\gamma_g - 1}\right) + \mathbf{u}\frac{\gamma_c P_c}{\gamma_c - 1} - \frac{\kappa_c \nabla P_c}{\gamma_c - 1},$$

$$Q = \mathbf{v_w} \cdot \nabla P_c.$$

What is v_w?

- Self confinement picture: Alfven waves amplifed by super-Alfvenic cosmic rays flowing down their pressure gradient.
  - $Q = |v_A \nabla_\parallel P_c|$.
- Extrinsic turbulence picture: Waves produced by an MHD turbulent cascade.
  - For balanced turbulence, $Q = 0$ & there is some Fermi acceleration.
  - For imbalanced turbulence, could be similar to self confinement picture.
- Long recognized that self confinement only works up to a certain energy.

Streaming Instability

Resonance condition

$$k \sim \frac{qB}{p\mu}$$

Higher energies resonate with longer wavelength waves, but as $\mu \to 0$, $k \to \infty$. Instability growth rate

$$\Gamma_c \sim \omega_{cp} \frac{n_c(> p_{min})}{n_i} \left(\frac{v_D}{v_A} - 1 \right).$$

Because of powerlaw energy spectrum, Γ_c declines with cosmic ray energy.

Damping Balances Growth

- Ion - neutral friction in weakly ionized regions: *typically eliminates coupling*.
- Nonlinear Landau damping on thermal ions: especially important in hot regions.
- Shearing apart of wave packets by background turbulence.

Marginal stability condition plus relationship between anisotropy & pressure gradient determines pressure profile & diffusivity κ_c. Self confinement works for $E < 100 - 200$ GeV for Milky Way conditions.

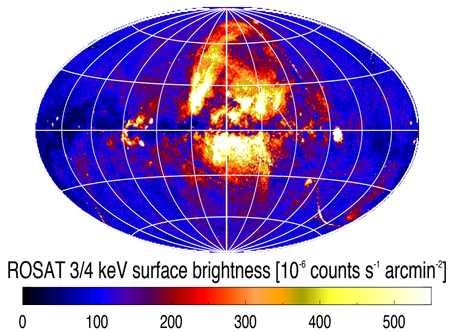
Wrinkles in the Picture

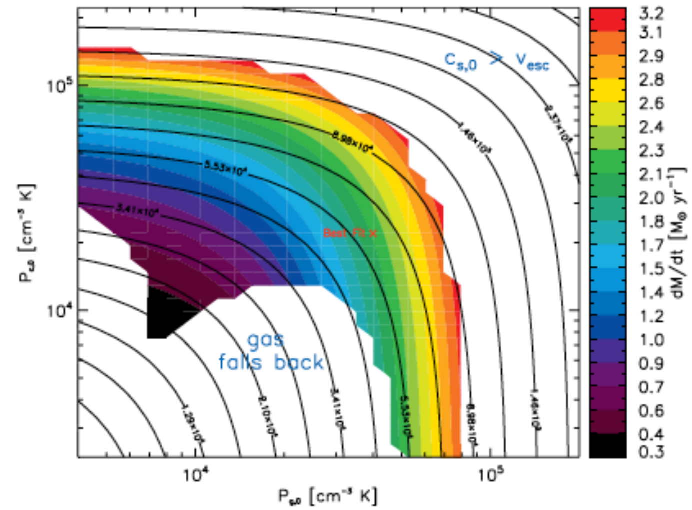
- Breakdown of diffusion theory as $\mu \to 0$; does $v_D \to v_A$? *addressed with mirroring by Felice & Kulsrud 1991*.
- Drastically modified waves and growth rates for $U_c/U_B > c/v_D$.
- Modification of Alfven wave dispersion relation for $\beta > (c/v_i)^2$.

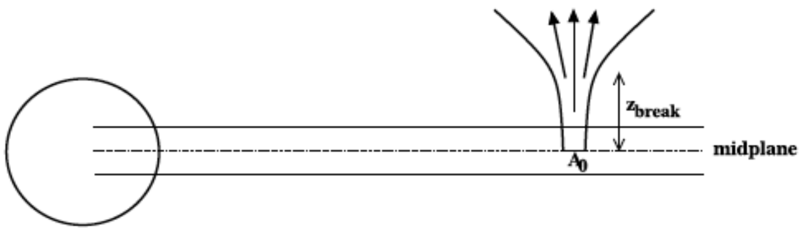
Extrinsic Turbulence

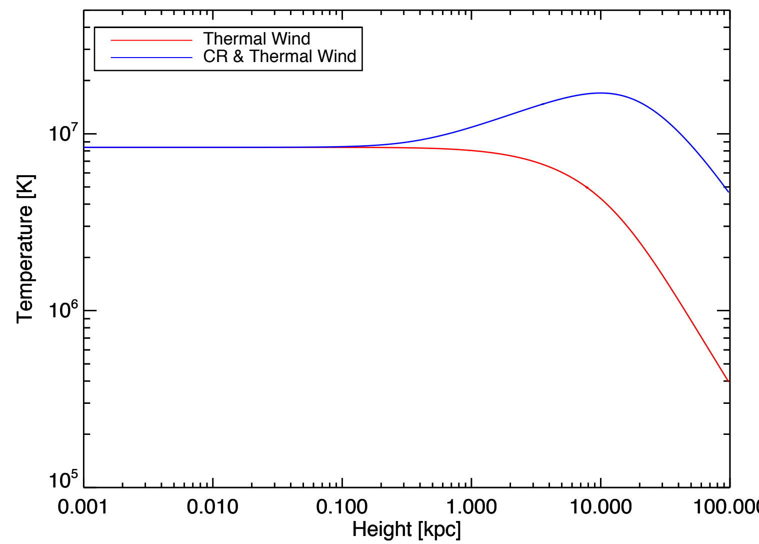
- MHD cascade is too anisotropic to scatter cosmic rays efficiently; compressive waves must be generated.
- If turbulence is balanced, cosmic rays extract energy from the background rather than donating energy to it.
- Long confinement times & low anisotropy requirements can be met, but requires a separate theory.

Galactic Wind







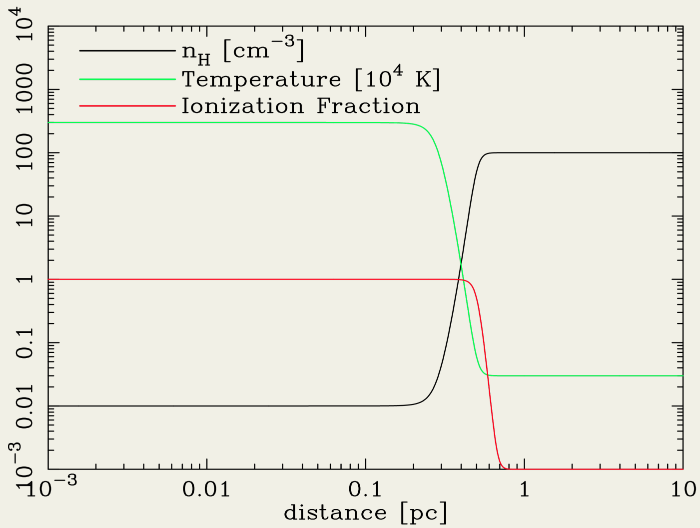


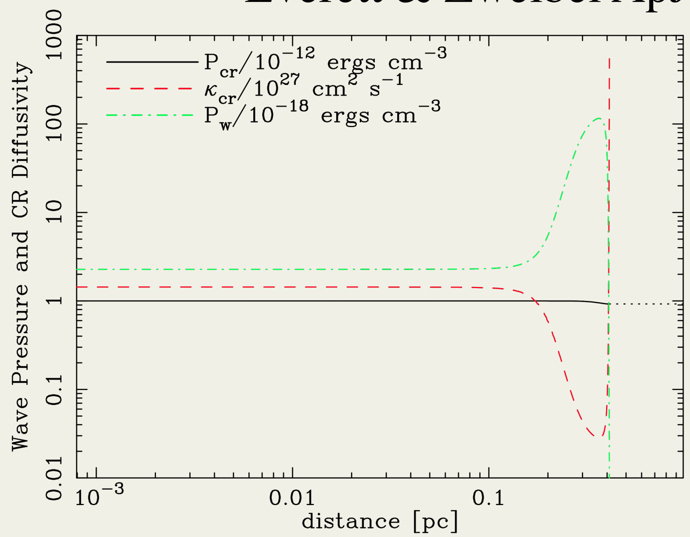
<u>Top left</u>: Soft x-ray sky,
<u>Bottom left</u>: Magnetic flux tube geometry.
<u>Top right</u>: Domains of flow, with mass loss rates
<u>Bottom right</u>: Gas temperature with & without cosmic ray heating.

Everett et al. 2008 ApJ

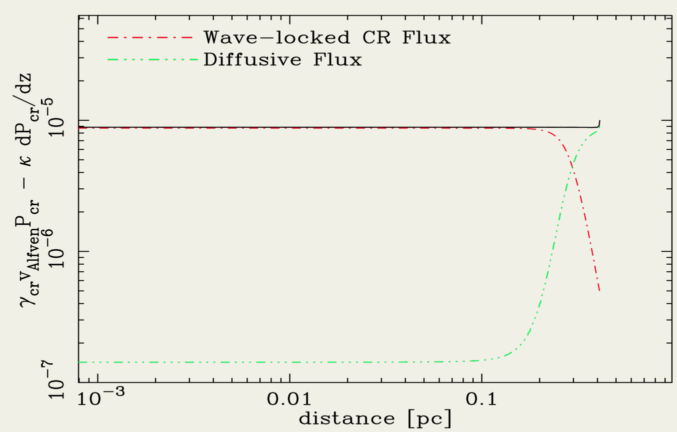
Cosmic Ray Coupling to Clouds

Everett & Zweibel ApJ 2011

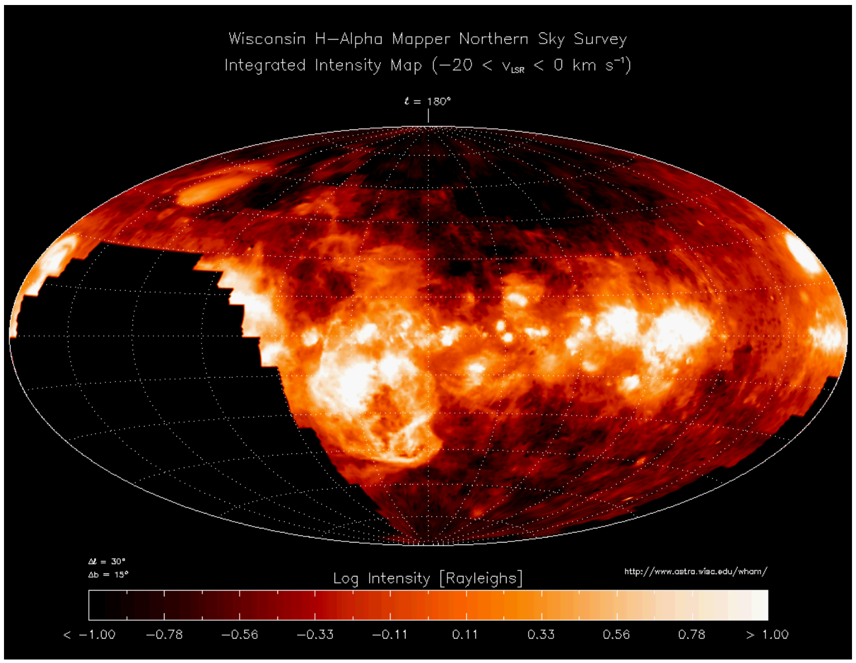


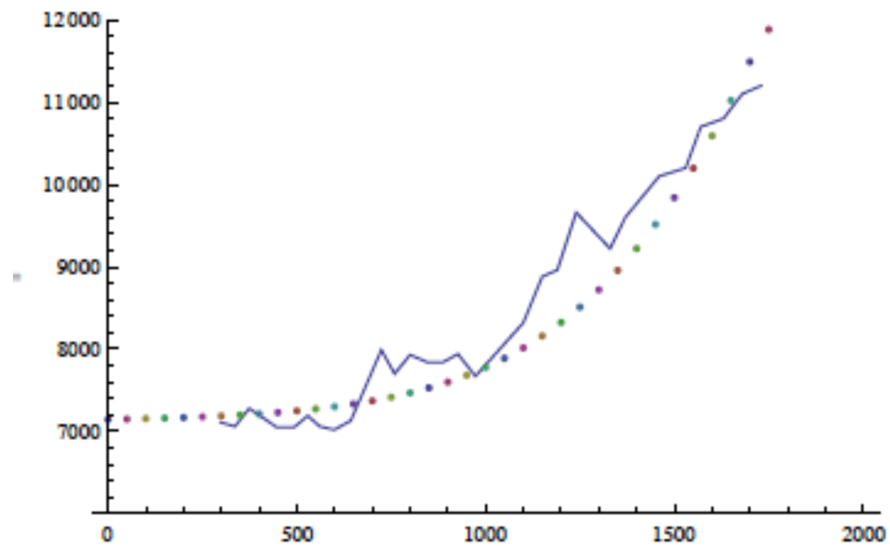


Top left: Model cloud setup. Top Right: Cosmic ray & wave pressure vs. depth. Bottom right: Transition from advection to diffusion, followed by free streaming -> **No force on the bulk of the cloud** .



Cosmic Ray Heating of Diffuse Interstellar Gas





Left: Galactic Ha emission, showing a thick layer of warm ionized gas. Right: Model of thermal equilibrium , including cosmic ray heating (Wiener et al. 2013)

Cosmic Ray Probes of Star Formation

- Can Milky Way-like models of cosmic ray acceleration by supernovae lead to the gamma ray and synchrotron emission observed in starburst galaxies?
- Are these galaxies calorimeters?
- What can we learn from about starburst galaxies by reproducing their spectra?

Tova Yoast-Hull, with Jay Gallagher , John Everett, & EGZ

Fits to the Gamma Ray Sprectrum of M82

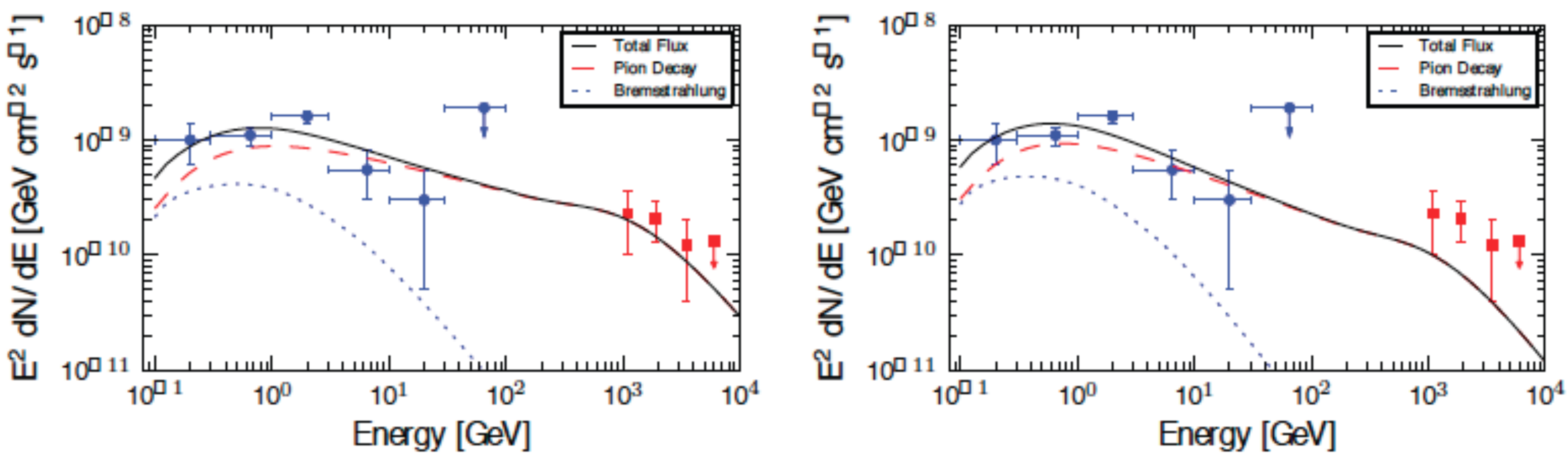
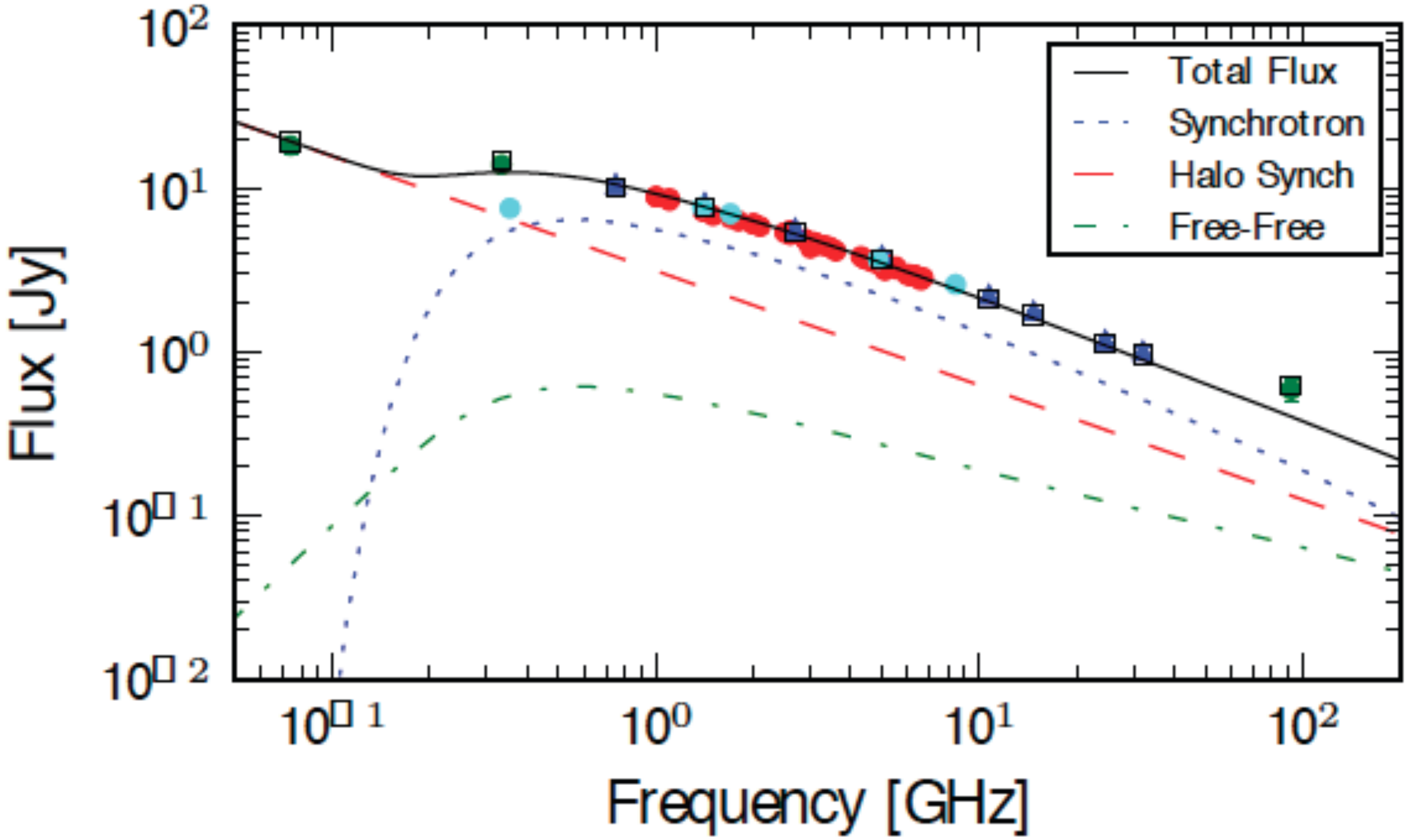


FIG. 5.— □-ray spectra. *Left:* □-ray spectrum with parameters $p = 2.1$, $M_{mol} = 4 \times 10^8$ $M_\odot$, $B = 275$ □G, $v_{adv} = 500$ km s^{-1}, $n_{ion} = 100$ cm^{-3}. This spectrum is the best fit to the □-ray data. *Right:* □-ray spectrum with parameters $p = 2.2$, $M_{mol} = 4 \times 10^8$ $M_\odot$, $B = 275$ □G, $v_{adv} = 400$ km s^{-1}, $n_{ion} = 150$ cm^{-3}. This is the □-ray spectrum that corresponds to the best radio fit for a spectral index of $p = 2.2$. The solid black lines represent the total □-ray flux, the dashed red lines represent the contribution from neutral pion decay, and the dotted blue lines represent the contribution from bremsstrahlung. □-ray data include: Ackermann et al. (2012) (*Fermi* - blue circles), Acciari et al. (2009) (VERITAS - red squares). Data with downward arrows represent upper limits for both Fermi and VERITAS data.

YEGZ ApJ 2013

Fit to the Radio Spectrum



Fitting Parameters

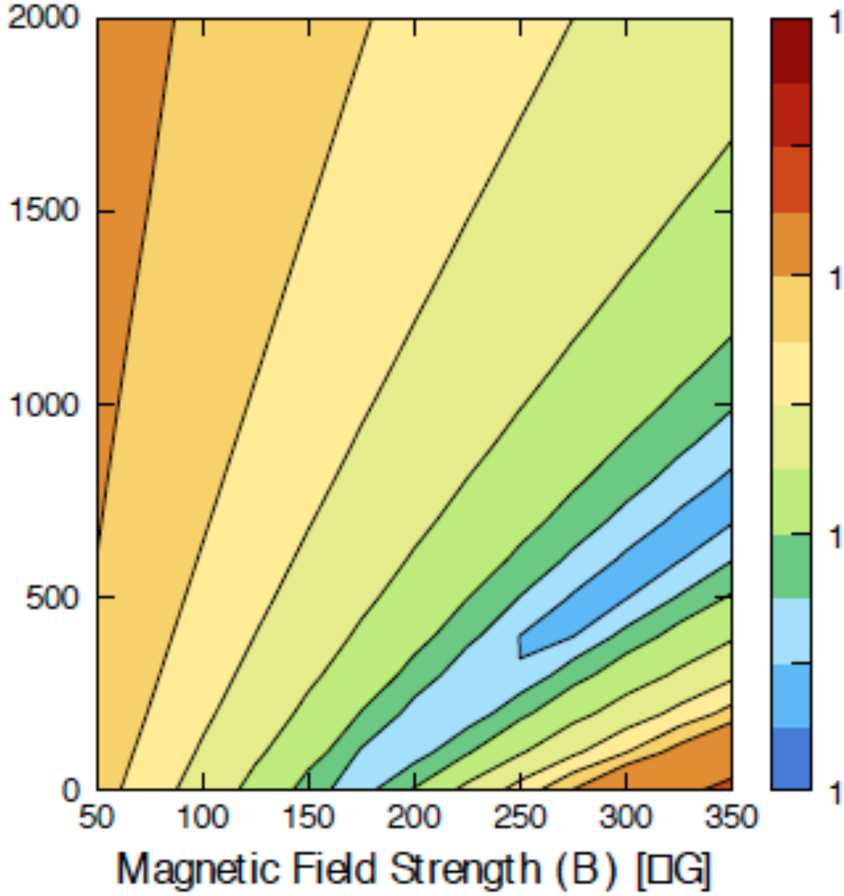


TABLE 3
BEST-FIT MODEL PARAMETERS

Physical Parameters	Best-Fit Value
Magnetic Field Strength (B)	275 □G
Advection (Wind) Speed (v_{adv})	500 km s^{-1}
Ionized Gas Density (n_{ion})	100 cm^{-3}
Spectral Index (p)	2.1
Molecular Gas Mas (M_{mol})	4×10^8 $M_\odot$

NOTE. — Results for $\square^2_{radio} = 22.6$, $\square^2_\gamma = 9.6$

M82 is an excellent electron calorimeter
And a ~50% proton calorimeter.

Conclusions

- The long confinement times & near isotropy of cosmic rays motivated a theory of self confinement and resulting fluid picture.
  - Not tested by numerical simulations (but soon to be).
  - Many devilish details in the implementation.
- Applications include galactic winds, ISM/ICM heating, etc.
- Cosmic ray acceleration & confinement theory can be tested in other galaxies.