# Effects of Partial Ionization

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

# Motivation

- Most interstellar gas is 1% ionized or less - down to $10^{-7}$.
- Photospheres & chromospheres of magnetically active stars are weakly ionized.
- Protoplanetary disks are *extremely* weakly ionized.
- Weak ionization leads to novel effects on magnetic transport, reconnection, turbulence, shear flow instability.
- There will be neutrals in MPDX.

# The Plan of This Talk

- Ion-neutral drift.
- Phenomena associated with weak ionization.
- Application to MPDX:
    - Neutrals in minority?
    - Importance of resistivity
    - Importance of Hall effect
    - High $\beta$ effects

# Plasma-Neutral Drift

Model force on neutrals by a friction term:
$\mathbf{F}_{ni} = -\rho_n \nu_{ni}(\mathbf{v}_n - \mathbf{v}_i)$, with

$$\rho_n \nu_{ni} = \rho_i \nu_{in} = \frac{\rho_i \rho_n \langle \sigma v \rangle}{m_i + m_n}.$$

For H-H, $\langle \sigma v \rangle \sim 10^{-9}$cgs. Response at frequency $\omega$:

$$\mathbf{v}_n = \frac{\mathbf{v}_i}{1 + i\omega\tau_{ni}}$$

# Limits

- $\omega\tau_{ni} \gg 1$: Neutrals stay in place, frictional damping of Alfven waves at rate $\nu_{in}/2$.
- $\omega\tau_{ni} \ll 1$: Neutrals almost move with ions, $v_A \rightarrow v_{Ai}(\rho_i/\rho)^{1/2}$, $\delta_i \rightarrow \delta_i(\rho/\rho_i)^{1/2}$, frictional damping $\propto \nu_{in}^{-1}$.

# In Astrophysics

Dubbed “ambipolar diffusion" by Mestel & Spitzer (1956). Assume weak ionization. On times $\gg$ ion-neutral collision time $\tau_{in}$,

$$\mathbf{J} \times \mathbf{B} = \rho_i \tau_{in}^{-1} (\mathbf{v}_i - \mathbf{v}_n).$$

Define $\mathbf{v}_D \equiv (\mathbf{v}_i - \mathbf{v}_n)$, $\mathbf{v} \equiv (\rho_i \mathbf{v}_i + \rho_n \mathbf{v}_n)/(\rho_i + \rho_n) \approx \mathbf{v}_n$.

# Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times (\mathbf{v}_D \times \mathbf{B}).$$

Expand:

$$\mathbf{v}_D \times \mathbf{B} = -\mathbf{J}\frac{B^2 \tau_{in}}{\rho_i} + \frac{\mathbf{J}\cdot\mathbf{B}\tau_{in}}{\rho_i}\mathbf{B}.$$

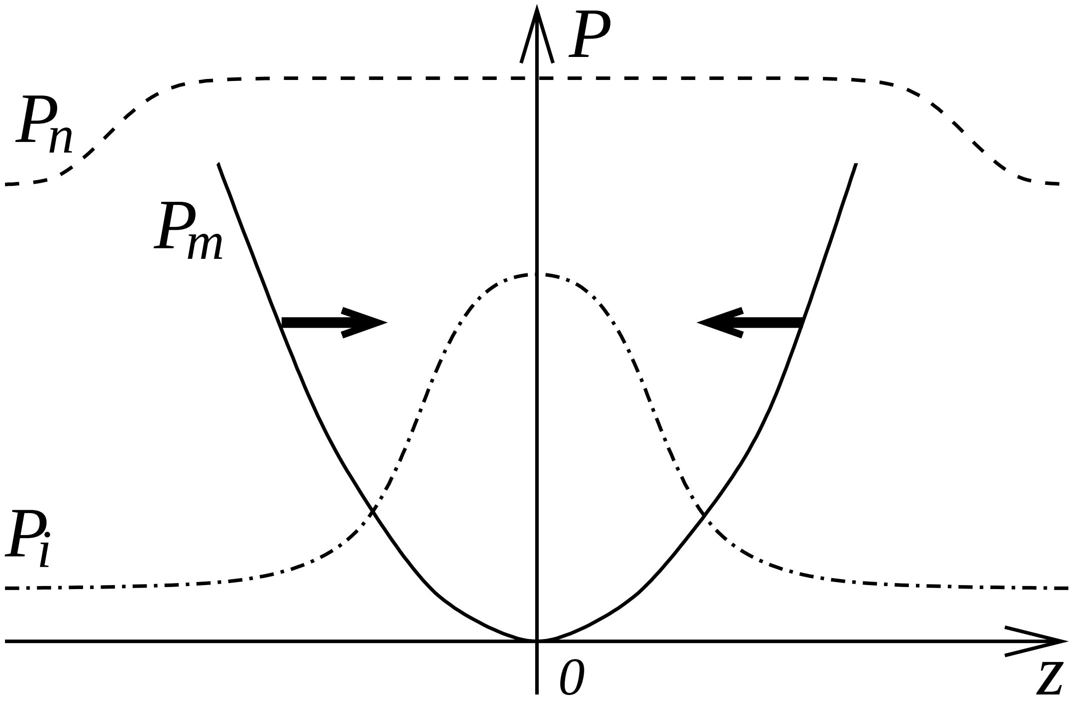
First term is diffusive w. diffusivity $\lambda_{AD} \equiv v_{Ai}^2 \tau_{in}$; second term is an “$\alpha$" effect; $\lambda_{AD}$ transports $B$ relative to the mass, but doesn’t change topology of $B$. See EGZ (1988) for $\alpha$ effect. Ambipolar Reynolds number $R_{AD} \equiv LV/\lambda_{AD}$ measures freezing of $B$ relative to the bulk fluid.

# Ambipolar *vs* Ohmic Diffusion

$$\frac{\lambda_{AD}}{\lambda_{Ohm}} = (\omega_{ce}\tau_{ei})(\omega_{ci}\tau_{in}) \sim 6 \times 10^{24} \frac{T_{eV}^{3/2} B^2}{n_i n_n}$$

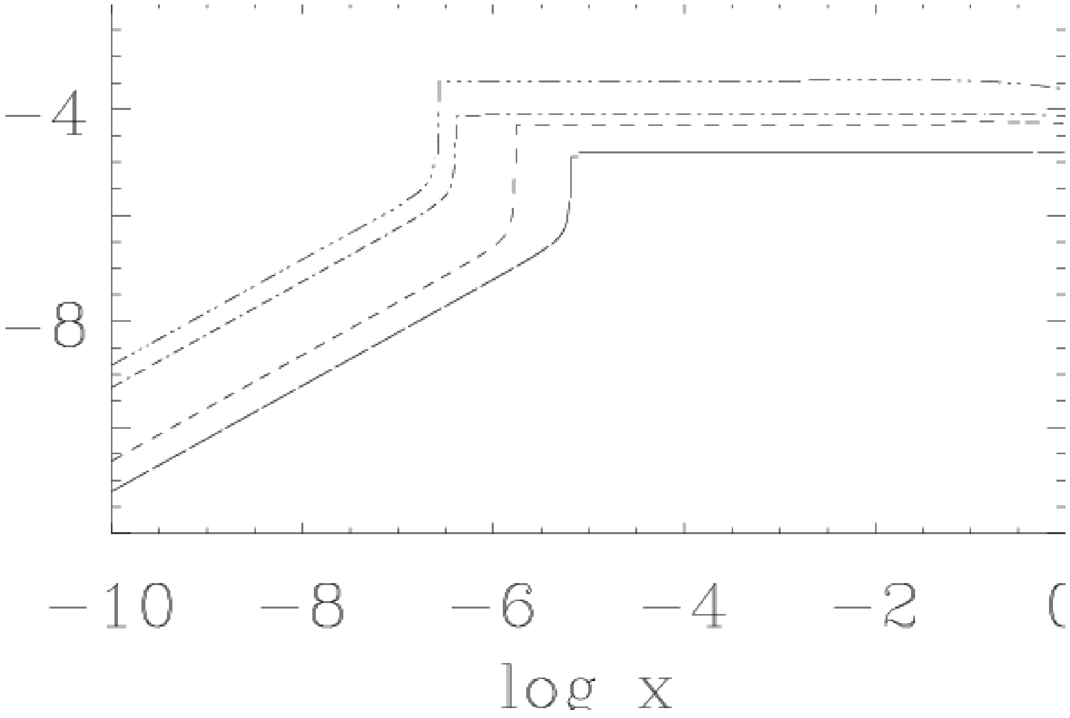
in a hydrogen plasma. If ions dominate this should be multiplied by $(\rho_n/\rho_i)^2$.

# Fast Ohmic Diffusion



The pressure gradient associated with a magnetic neutral sheet self-steepens due to the inward force on the ions. In an ideal medium steady state profile would be $B \propto x^{1/3}$. Recombination removes ions, leading to fast reconnection (E. Heitsch & EGZ 2003a).

# Sharp Profiles



Log of ion inflow speed as a function of log position in a few of our models. Note the extreme range of scales.

# Reconnection Rate

In the limit of fast recombination, the reconnection rate is given by

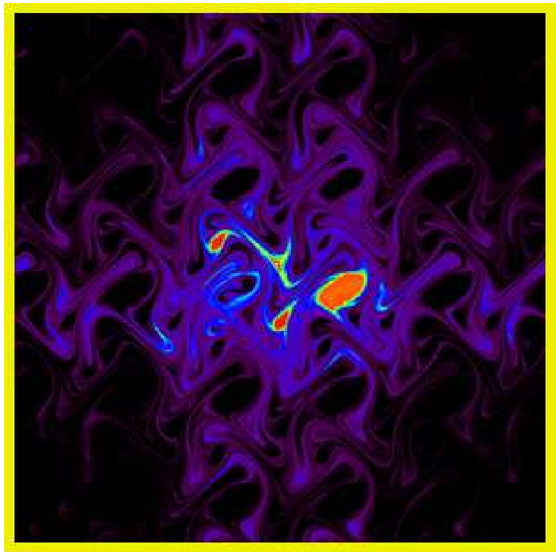
$$v_{rec} \sim v_{SP} \left( \frac{L}{v_A \tau_{rec} \beta^{3/\gamma}} \right)^{1/2} .$$

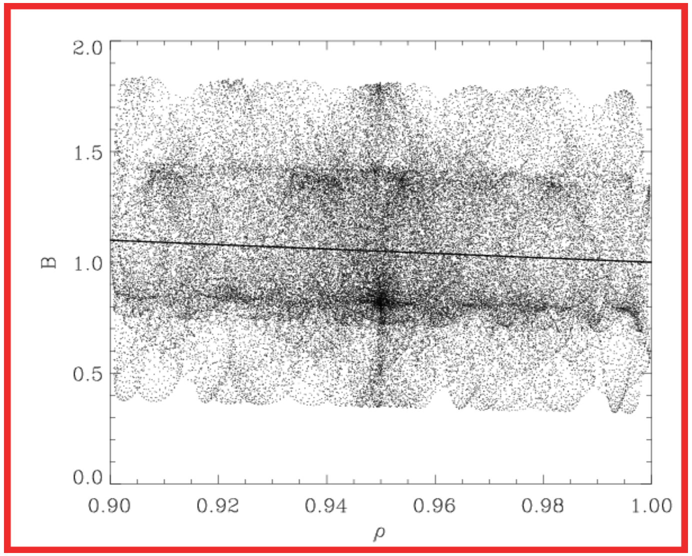
That is, the time for ions to flow out of the region is replaced by the (much shorter) time for ions to recombine.

# Effect of a Guide Field

If the field is sheared instead of nulling, the recombination trick does not work, and we are back to slow reconnection. This is the generic case (FH & EZ 2003b). Standard tearing mode theory gives usual scaling with $\lambda_{Ohm}$ with $v_A$ or $v_{Ai}$ depending on collisionality (EGZ 1989).

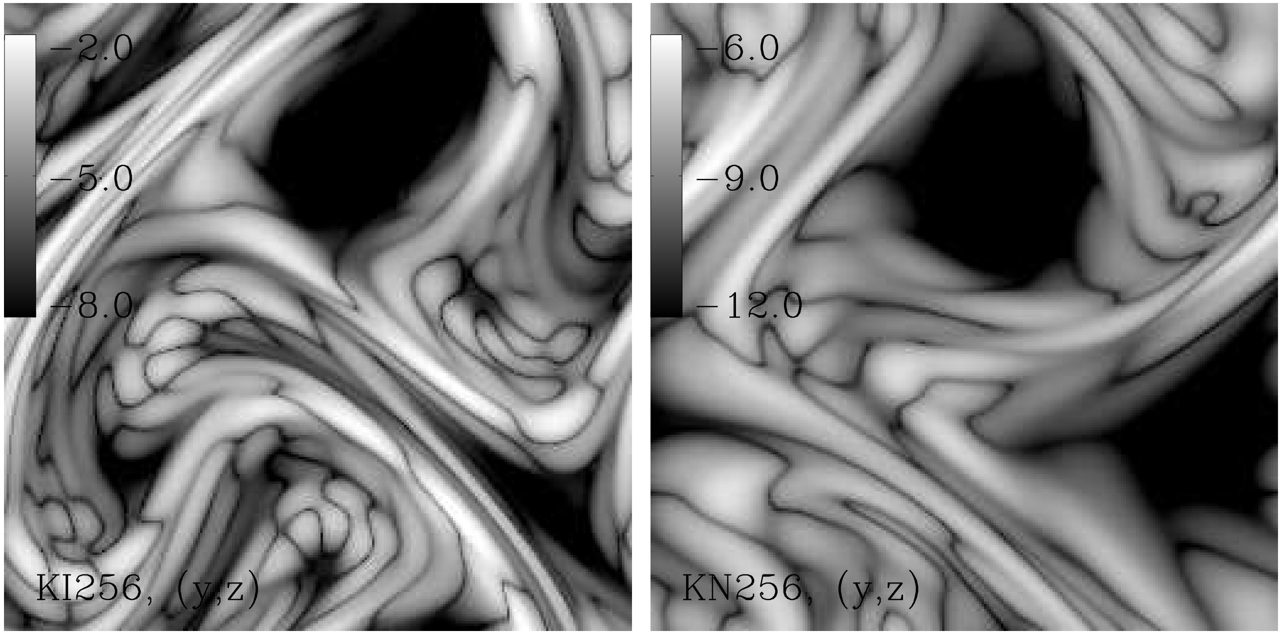
# Turbulent Diffusion





In a weakly ionized, turbulent medium small scale ion-neutral drifts are set up, quickly transporting the field relative to the neutrals. This is a mechanism of diffusive transport. EGZ 2002, FH, EGZ et al. 2004. Flow is the Galloway-Proctor (1992) 2D cellular time dependent chaotic flow.

# Effect on Dynamos



Left: fieldstrength in the G-P flow. Right: same, except plasma flow is frictionally forced by G-P flow but nonlinearly modified by magnetic forces. Smallest scales eliminated, but growth rate reduced (note contour levels). From EGZ & FH 2008.

# Waves

Dispersion relation for waves propagating parallel to $B$:

$$i\omega + \lambda_{Ohm}k^2 - \frac{ik^2v_{Ai}^2}{\omega\left(1+\frac{\nu_{in}}{i\omega+\nu_{ni}}\right)} \pm i\omega_{ci}k^2\delta_i^2 = 0.$$

Ion-neutral friction, Ohmic diffusion, & the Hall effect are here.

# In MPDX

Are ions & neutrals coupled on Alfven timescales if highly ionized?

$$\nu_{ni} \sim 10^{-9} n_i \sim 10^4.$$

$$k v_{Ai} \sim 7 \times 10^2 B.$$

Coupling is good.

# Weakly ionized

Say $n_n \sim 10^{13}$, $n_i \sim 10^{11}$. Then

$$\nu_{ni} \sim 10^2,$$

$$kv_{Ai} \sim 7 \times 10^3 B.$$

Coupling is weak, frictional damping is strong.

# Summary

- In weakly ionized gases, friction with neutrals leads to nonlinear diffusion of $B$ with implications for magnetic field reconnection, transport, & Hall physics. Most interesting regime is highly collisional, strong coupling regime. This regime would be difficult to recover in MPDX.
- What happens at high $\beta$? Is $m_i$ effectively increased, increasing $r_i$? How important are frictional losses?