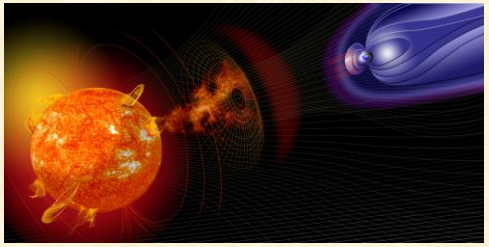
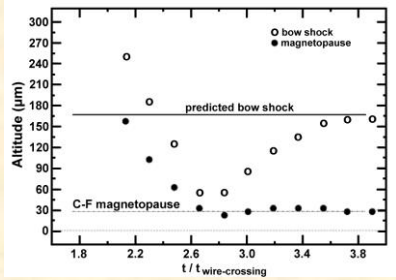
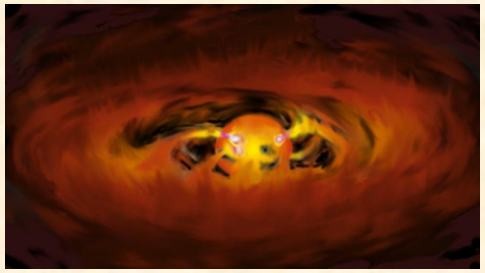
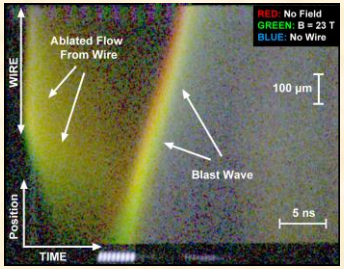
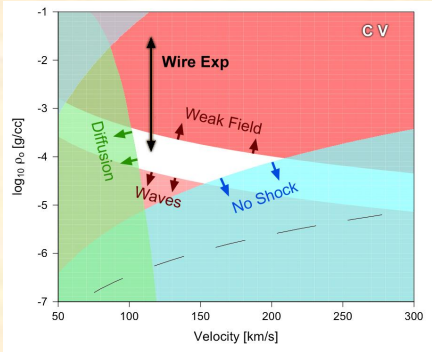
Magnetized Accretion Shocks and Magnetospheres in the Laboratory

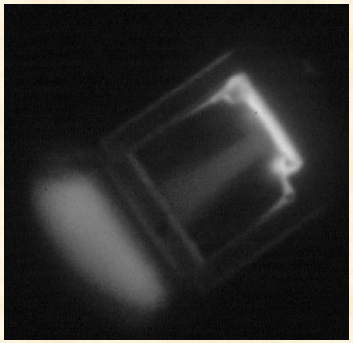












Observational Astronomy: Patrick Hartigan (Rice)

Numerical Simulations: Peter Graham and Paula Rosen (AWE), Adam Frank, Eddie Hansen (Univ. Rochester), Andy Liao (Rice)

Laboratory Experiments at Omega: John Foster (AWE), Gennady Fiksel (LLE), Gianluca Gregori (Oxford), Rachel Young and C. Kuranz (Michigan) C-K. Li (MIT)

NASA HST/DOE NNSA NLUF

Talk Outline

- Necessary Requirements to See Magnetic Effects in Shock Waves at Omega
- Experimental Efforts to Date : Three Astronomical Examples of Magnetized Supersonic Flows

Goal: To use laboratory experiments and numerical models as a means to understand the physics of supersonic MHD astrophysical flows

Requirements for all Magnetic Experiments

- **We need to have a shock** (λ_{mfp} < obstacle size)
  ion-ion collisions set mfp: $\lambda \sim \rho^{-1} V^{-4} Z^{-4} A^{3} (\ln\Lambda)^{-1}$

- **The field cannot be too weak**. $\beta_{ram} = \rho V^2 /(B^2/8\pi)$ determines how important the field is in the dynamics. Smaller is better but β_{ram} can't be too small or we get a magnetic wave. The Alfvenic Mach number $M_A = (\beta_{ram}/2)^{1/2}$ needs to be <~ 5 to see magnetic effects, and >~ 2 to have a reasonably strong shock.

- **The field cannot diffuse out when compressed**. Want magnetic Reynolds number $Re_{mag} = VL/\eta > 1$, where η is the magnetic diffusivity. Setting $Re_{mag} = 1$ defines a diffusion length scale that needs to be smaller than the obstacle size. $Re_{mag} \sim L V^4 (Z+1)^{-3/2} A^{3/2} (\ln\Lambda)^{-1}$

- **The material must be a normal plasma**. That is, there must be at least a few particles N_D in the Debye sphere so it is not strongly-coupled.

Boundaries for the Experimental Criteria

- **We need to have a shock:** Err on the side of caution for this one. We must be able to see a shock for the experiment to be relevant. Take the **λ_{mfp} < 30 μm**. This is comfortably less than the typical effects we expect to see in the experiments.

- **The field cannot be too weak**: This constraint is a bit more malleable. Certainly we want a strong field, but simulations often still show magnetic effects when $M_A = 5$ ($\beta_{ram} = 50$). So we choose **$2 < M_A < 5$** as the range.

- **The field cannot diffuse out when compressed**: This one is similar to β_{ram} in that it affects the field strength. Choose **$L_{diff} = \eta/V < 100$ μm** for now. A larger experimental setup helps.

- **The material must be a normal plasma**: Not a limit we want to approach. Strongly-coupled plasmas are quite different from the astrophysical analogues we seek. Require **$N_D > 3$** here.

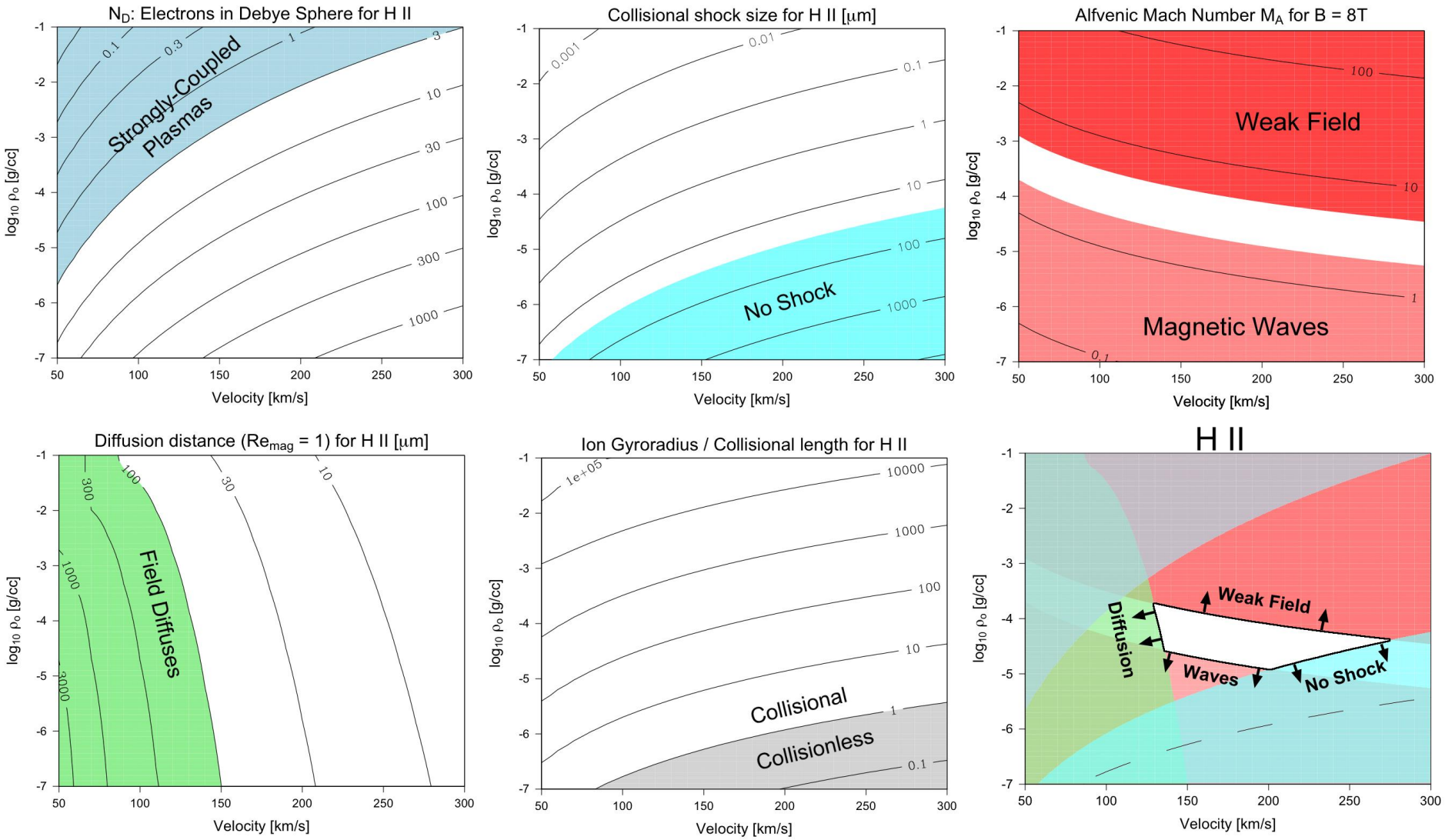
Other Considerations

- It would be good if the viscous **Reynolds number was > 1000** or so to make the postshock flow turbulent. Not critical to see dynamical effects of magnetic fields on shocks though

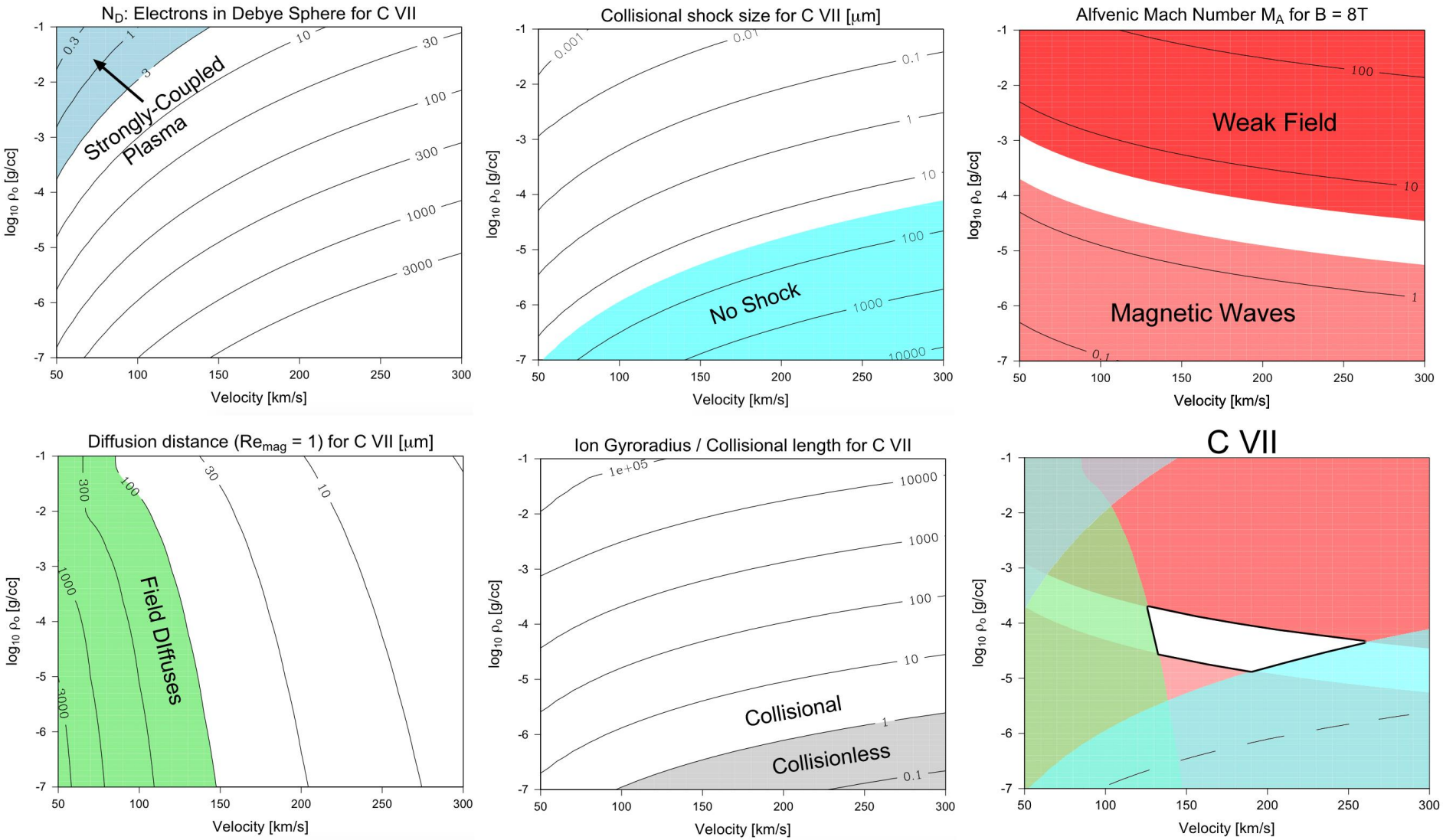
- Similarly, a **Peclet number > 1** ensures thermal conductivity is small in the postshock gas. Also not critical.

- Having the material be **optically thin** to free-free radiation helps with diagnostics

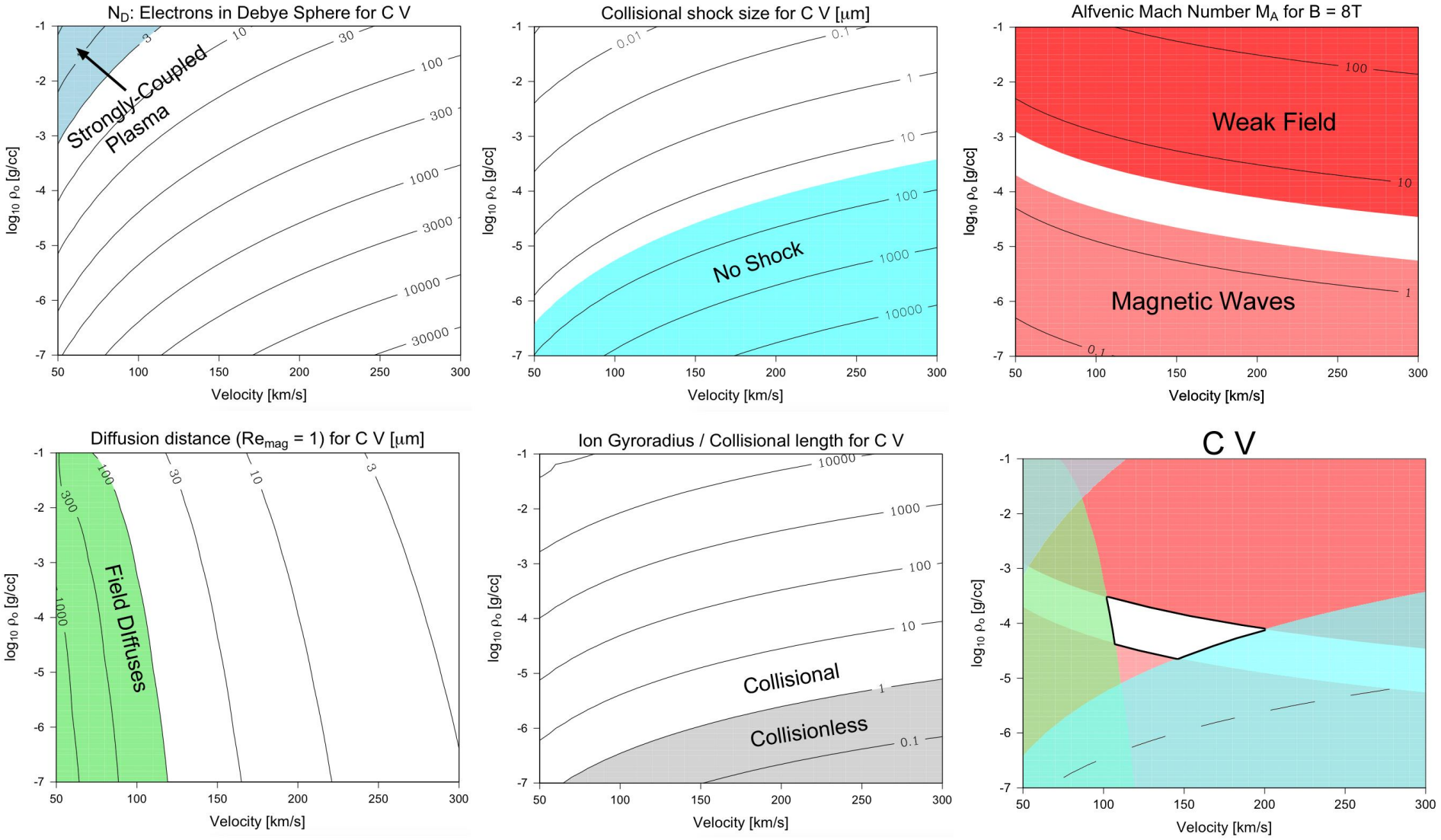
Reynolds number, Peclet number and optical depth we should consider after the range of the other parameters are determined



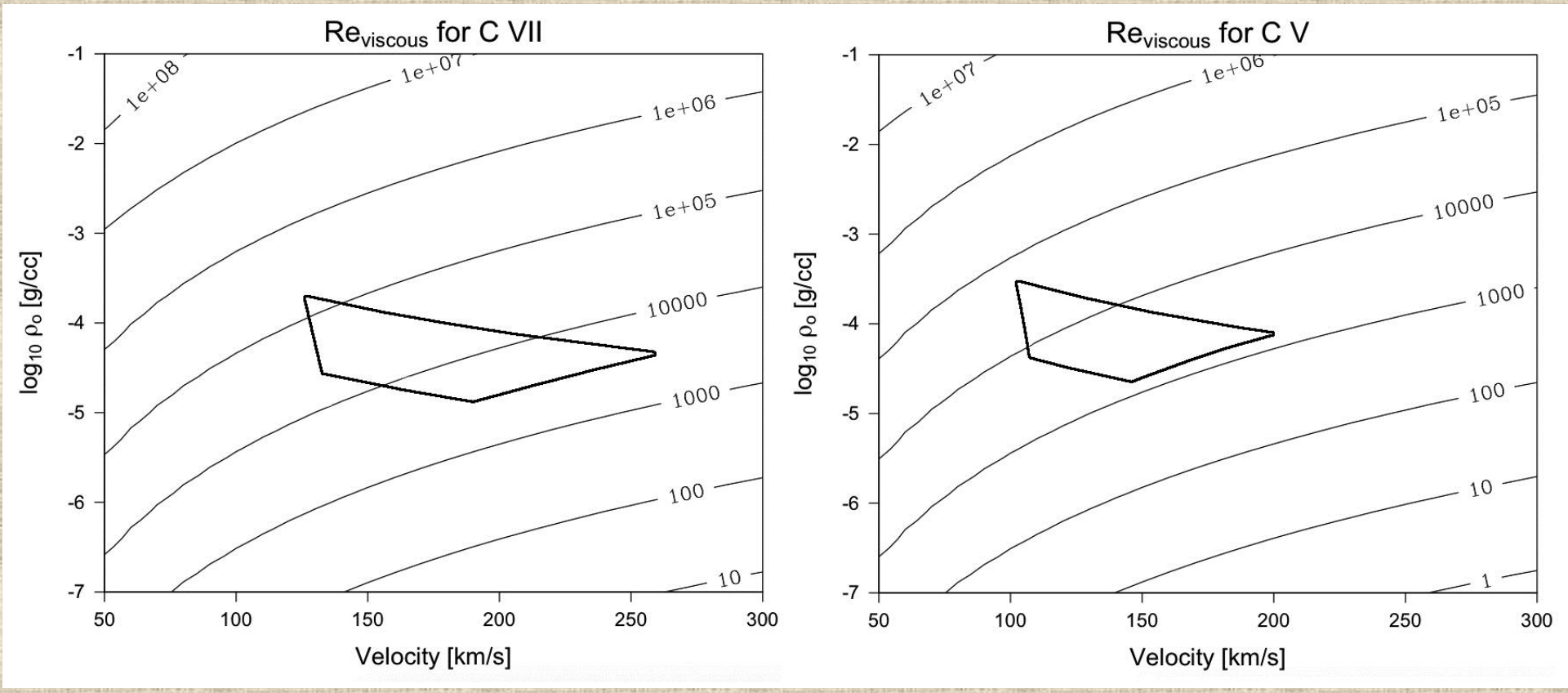
It is possible to satisfy the constraints



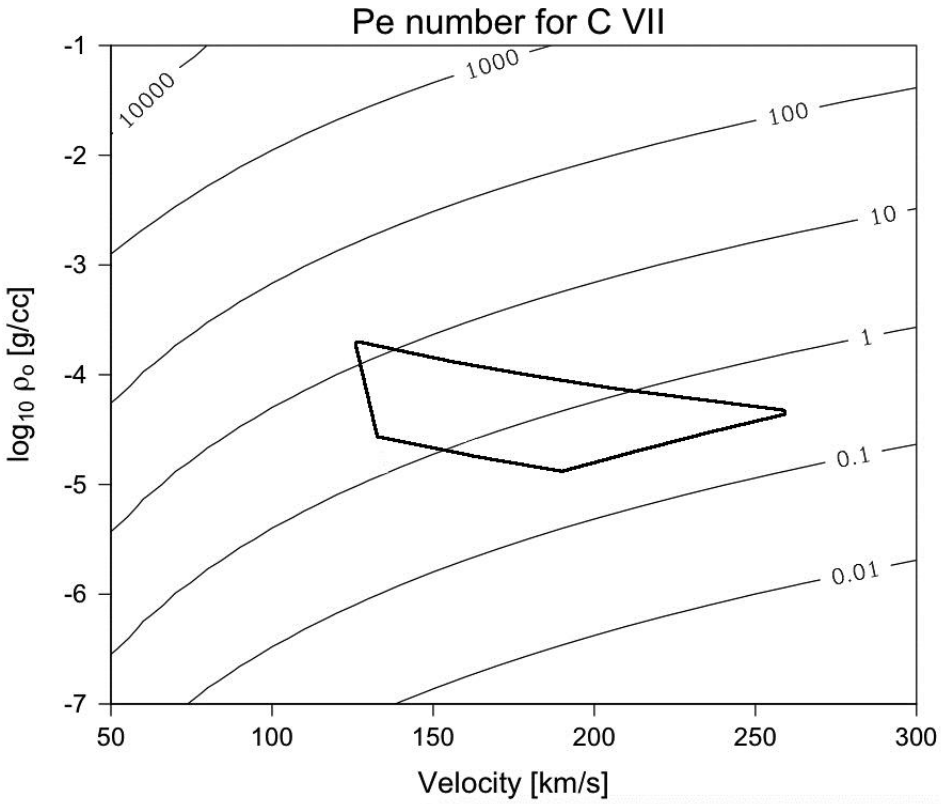
Fully-Ionized C looks a lot like H II

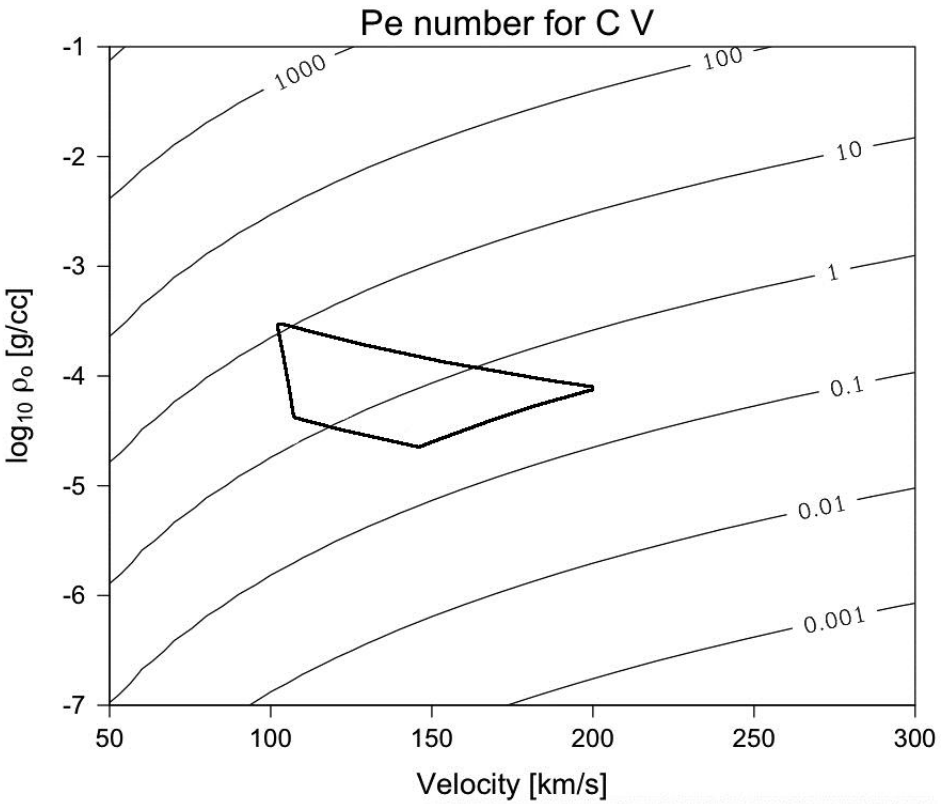


C V shifts to lower velocities



Viscous Reynolds Numbers are ~ 10,000





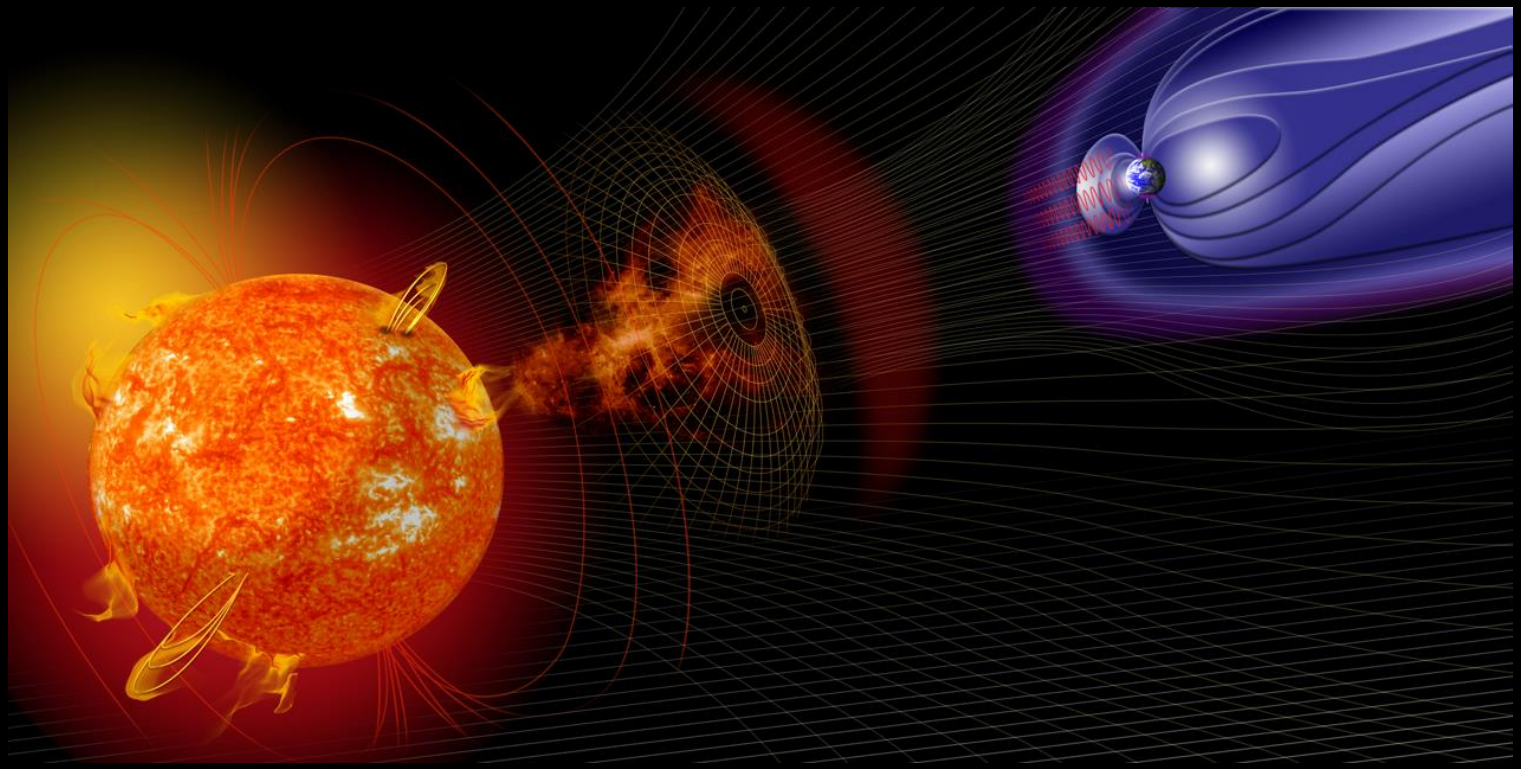
Peclet Numbers are ~ 1

Improve as one moves away from boundary where shock disappears

Parameter Summary

- Diffusion rules out low shock velocities
- Weak magnetic fields rule out high velocity/high density
- Large λ_{mfp} (no shock) rules out high velocity/low density
- Solutions exist for highly-ionized C around 100-200 km/s and 10^{-4} g/cc
- Shocks are collisional
- Viscosity looks small
- Thermal conductivity becomes more important the closer the parameters approach the boundary where the shock disappears

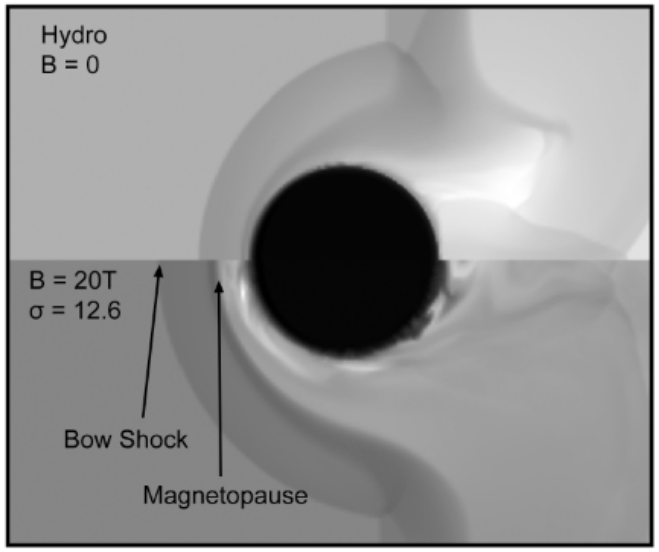
Planetary Magnetospheres

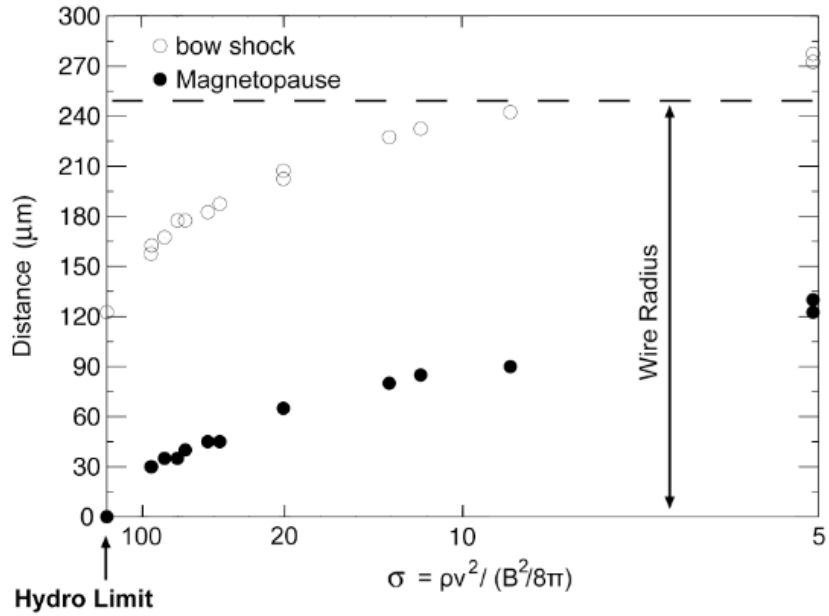


Credit: NASA

Experiments: Temporal Behavior; Concept Demonstration

Wire Experiment

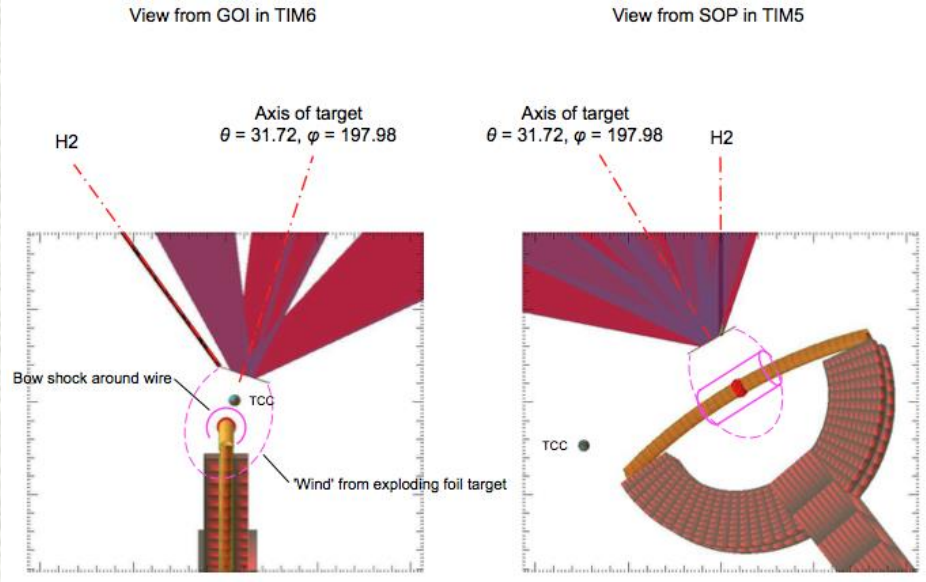




Concept: Magnetic Field from a wire is compressed from a supersonic flow. Analogue of a magnetosphere

MHD Numerical Prediction: Even relatively weak fields should affect position of standing shock.

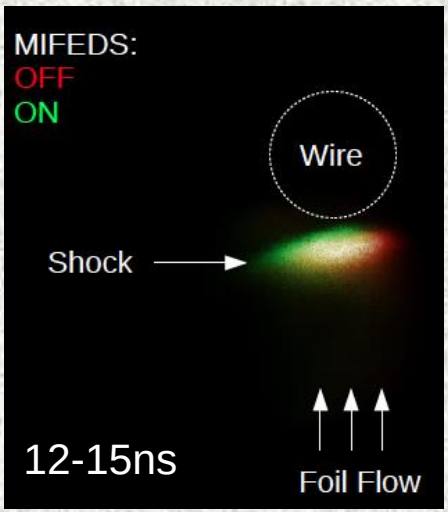
Details: 4-8T field from wire, 120 km/s flow from ablated CH disk. Models show density increases from $\rho \sim 10^{-4}$ g/cc to $\rho \sim 0.05$ g/cc

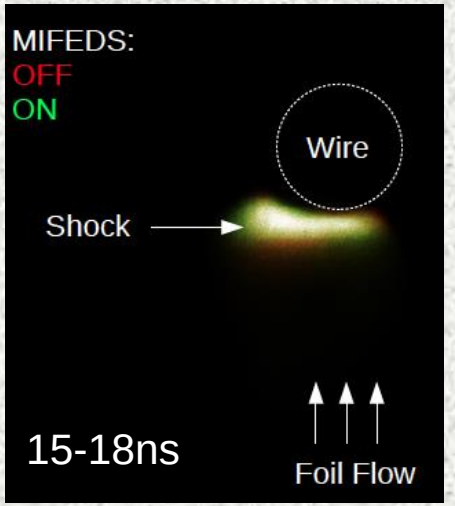


Wire Experimental Results

Parameters

- V = 80 km/s [measured from SOP]
- ρ = 1.6 mg/cc
- CH flow, assume as C^{+4} for illustration
- B = 7 T





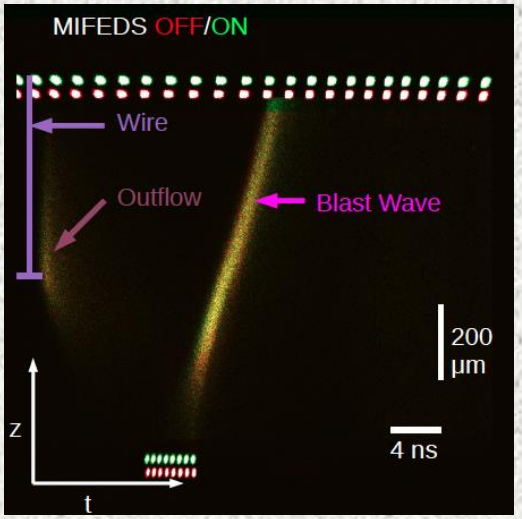
Images aligned precisely from preshot data

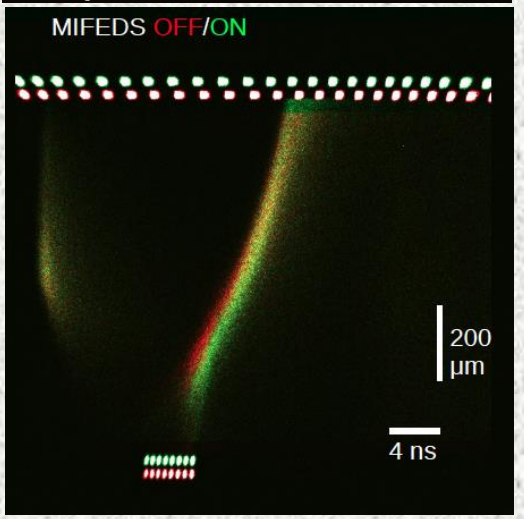
TPDI Images show what appears to be a shock around wire
No effect from the field

SOP shows bright emission continues past wire
Field effects are small, but in the right sense for SOP
Ablation from wire is complication

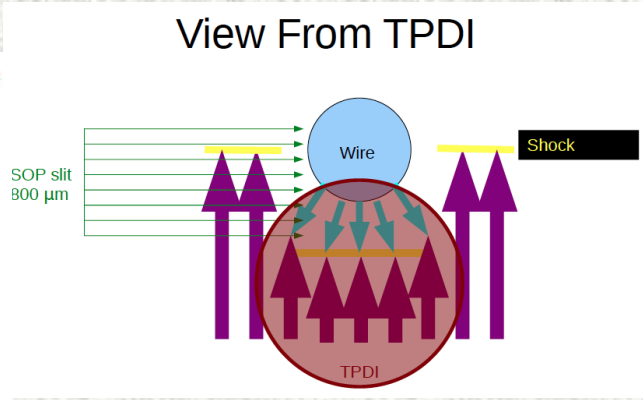
Experimental Results

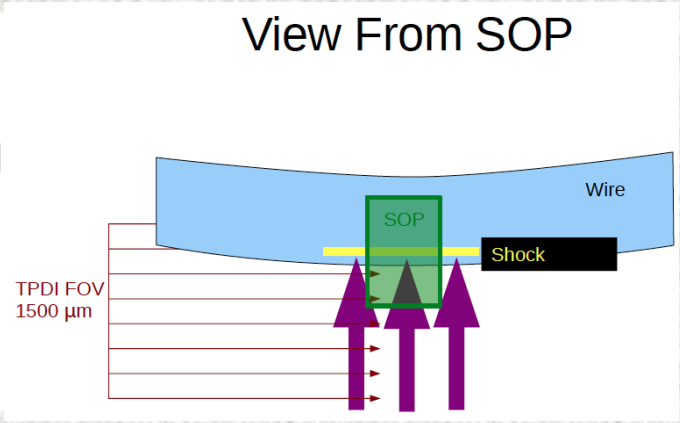
See shock in TPDI
No clear shock in SOP
No clear B field effect





Wire Experimental Results Explained





The SOP line-of-sight includes blast wave as it flows around the wire, and the TPDI images do not. This may explain why the shock is not visible in

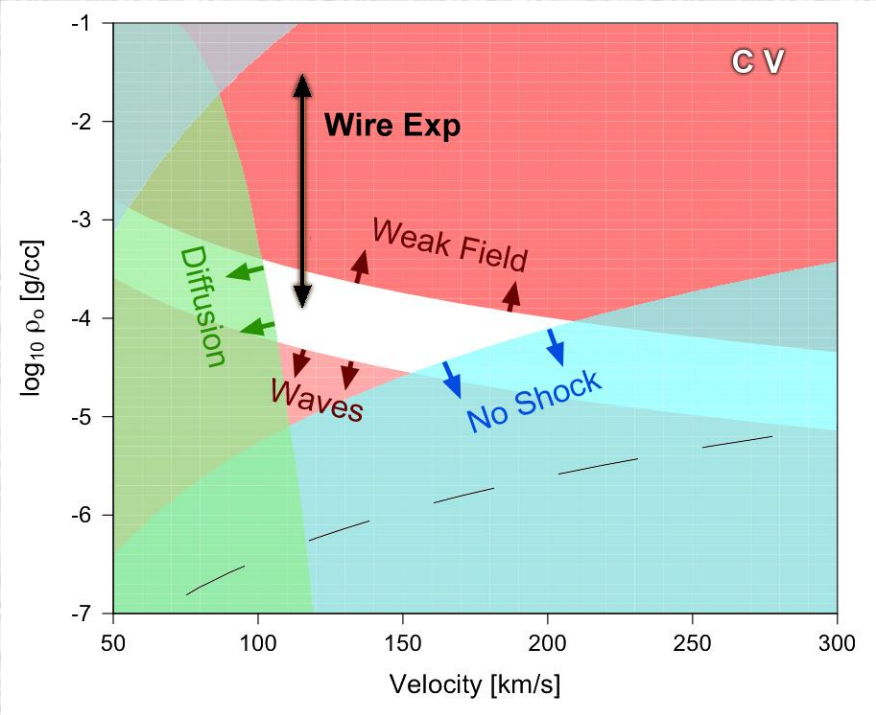
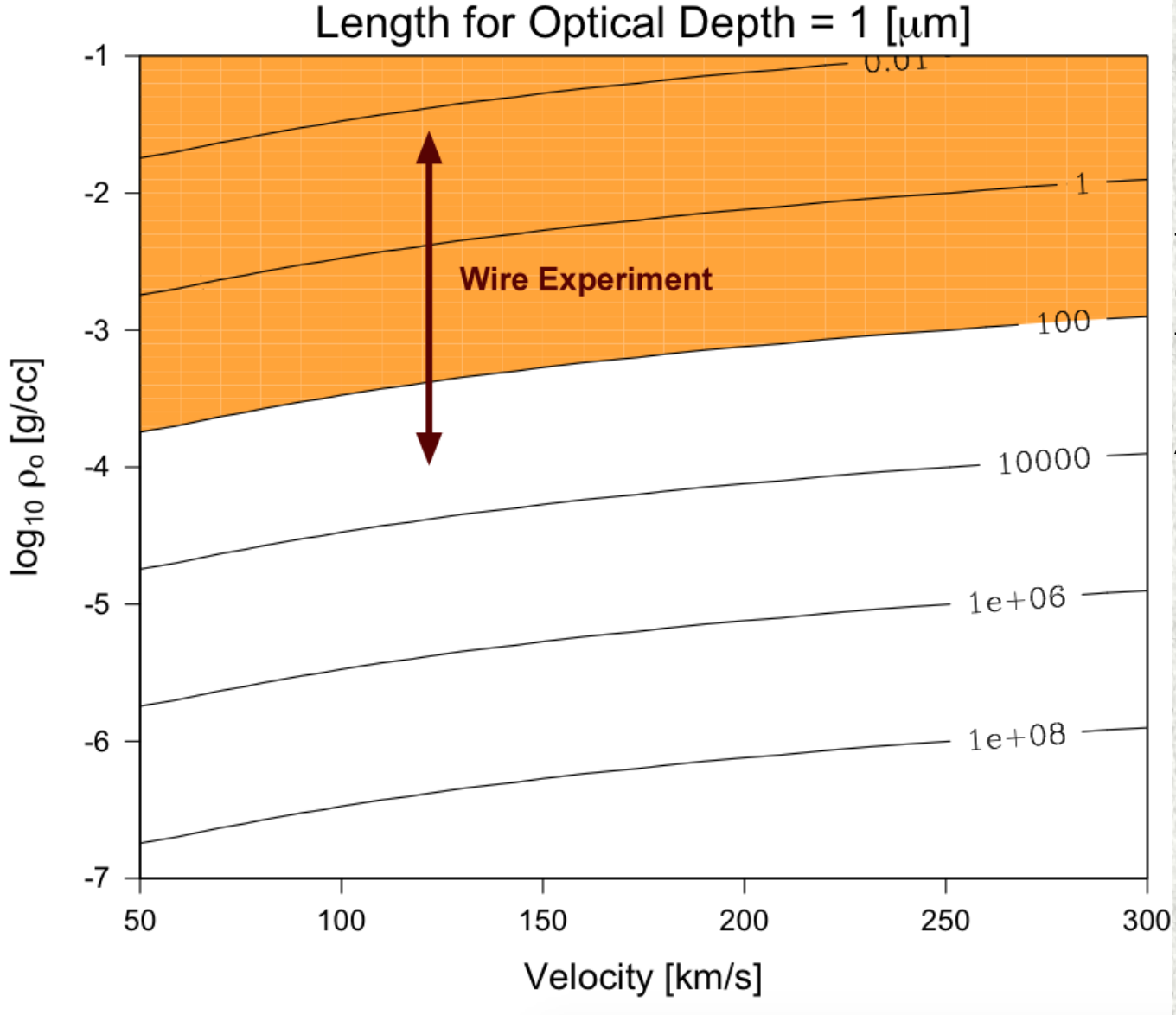


Diagram shows we expect a shock to form, but the density is too high

MHD codes not reliable here
Multifluid codes needed

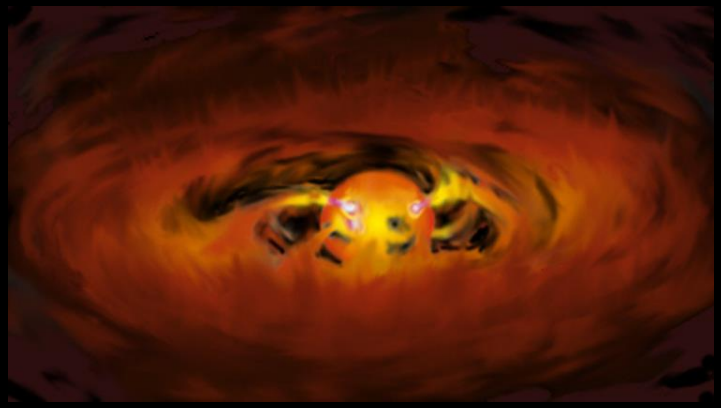
Opacity to Bremsstrahlung



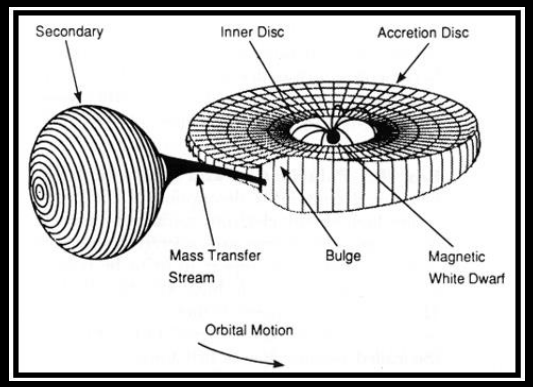
Much of the plasma in the wire experiment is optically thick to free-free radiation

Affects SOP data more than TPDI

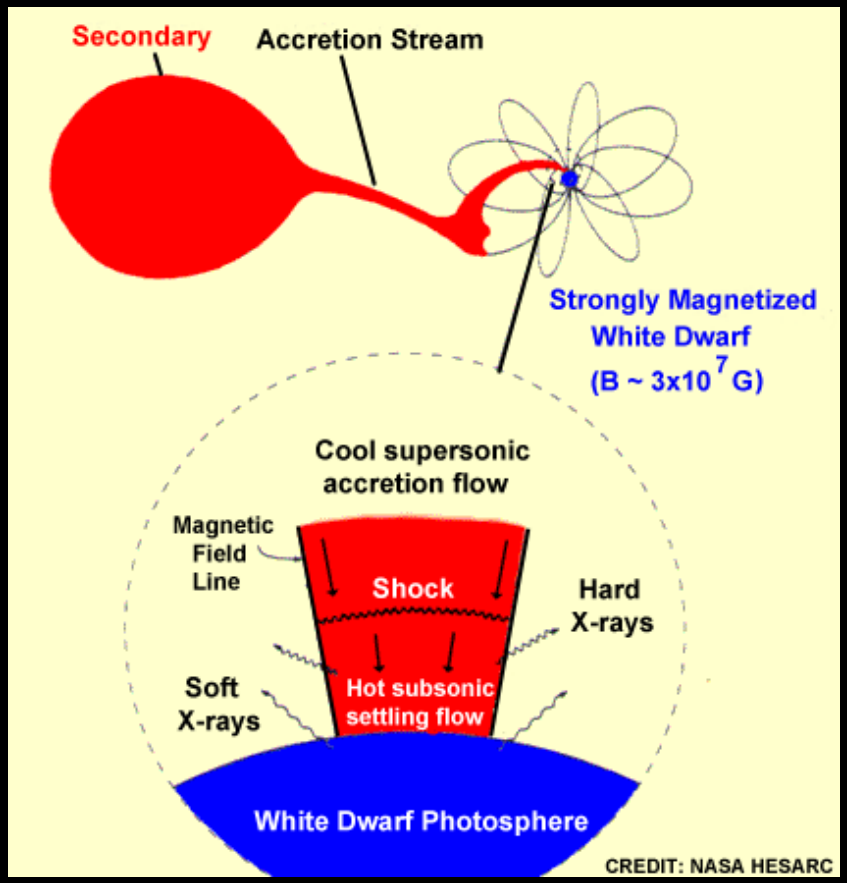
Accretion Columns



Accreting Protostars (T Tau)



Intermediate Polars (DQ Her)



Cataclysmic Variable Binaries
Polars (AM Her)

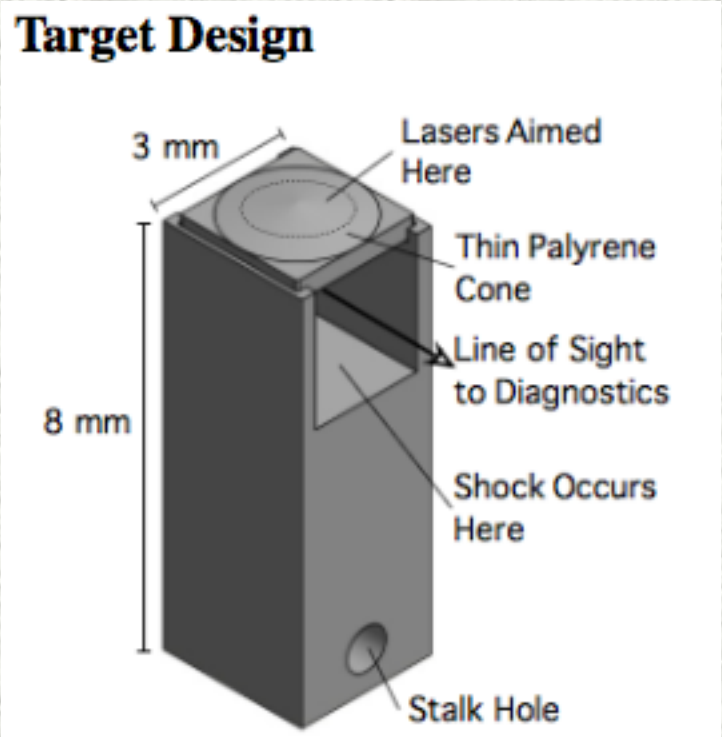
Experiments: Geometry of Accretion Shocks

Accretion Column Experiment

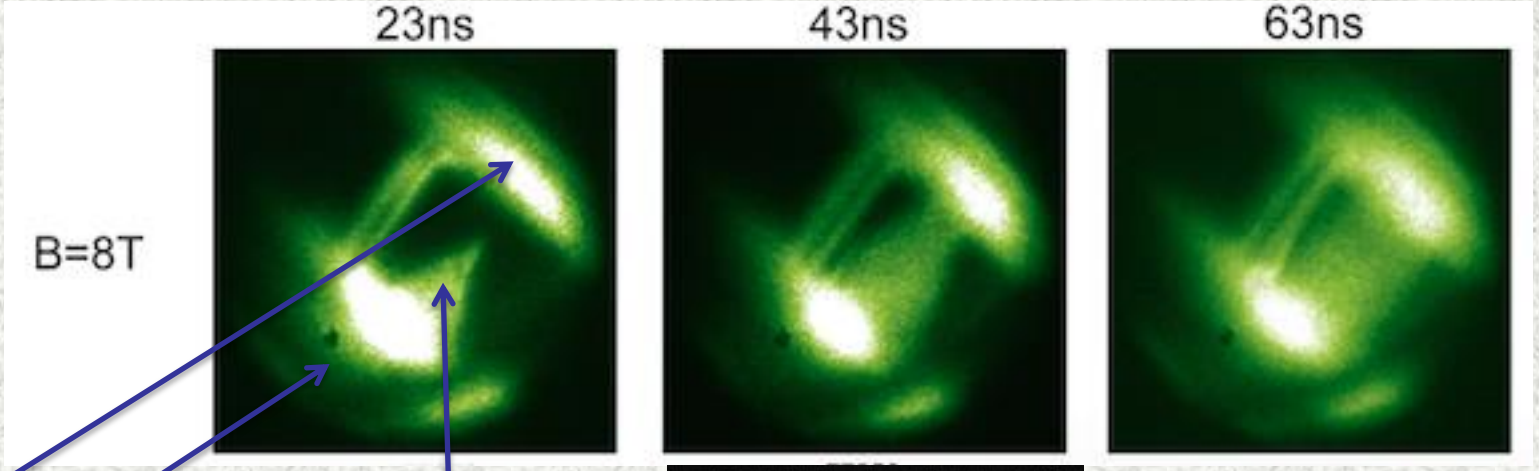
Concept: Drive a jet of plasma onto a block and observe the evolution of the shock that forms. Compare with and without a magnetic field

Several astrophysical applications, including T Tauri stars, CV's

Details: 4-8T field from MIFEDs coils. Thompson scattering data (April 2012) indicates flow impacts initially with Velocity ~ 250 km/s, density $\rho \sim 10^{-6}$ g/cc, dropping to 120 km/s and $\rho \sim 3\times10^{-5}$ at later times.

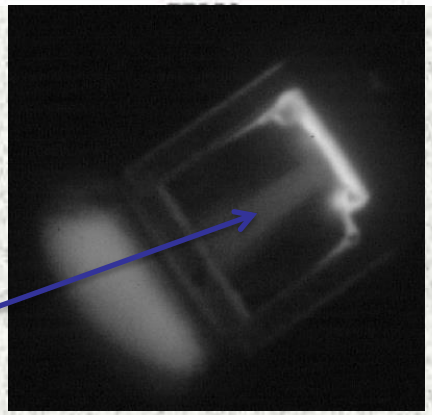


Accretion Column Experimental Results



MIFEDs Coils

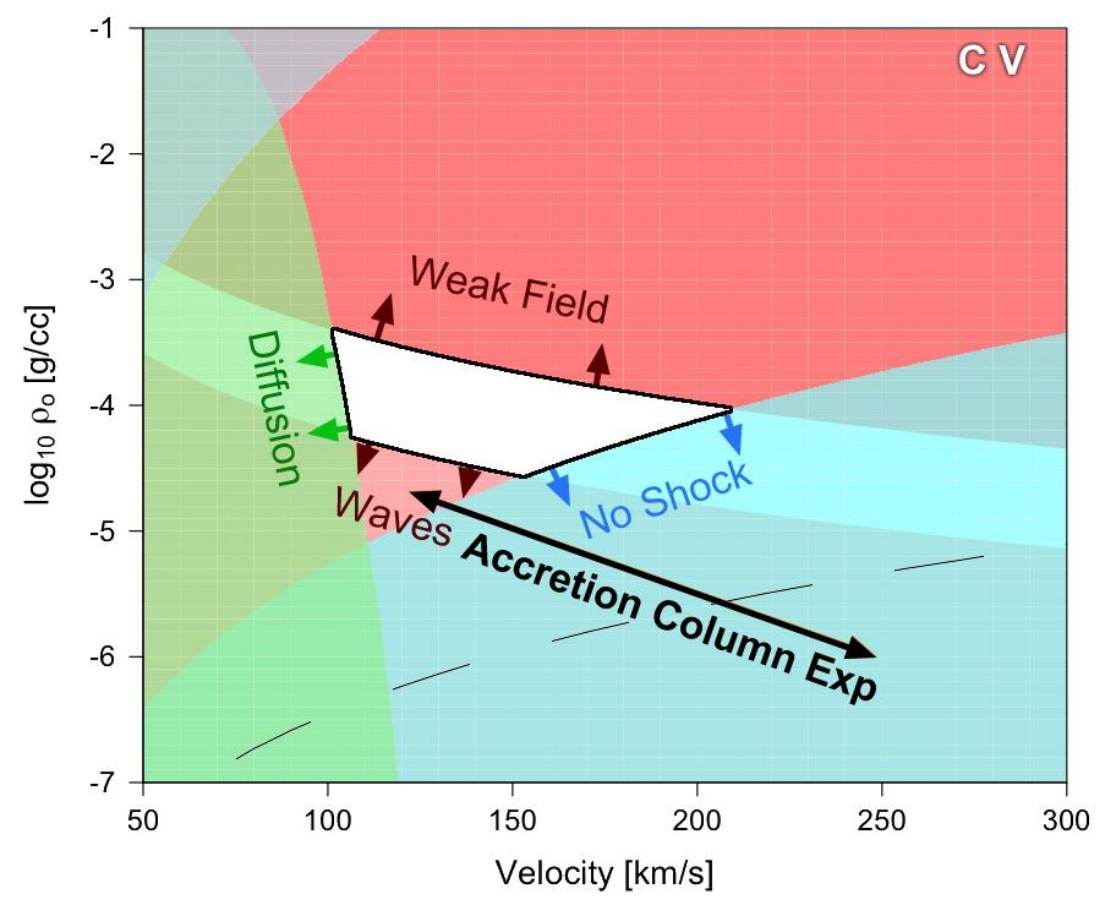
Flow



B=0 43ns

Accretion Shock not clearly visible for B=0 or B=8T

Accretion Column Experiment Explained



The densities/velocities in this experiment place it in a regime where we would not expect a shock to form except when flow was most dense

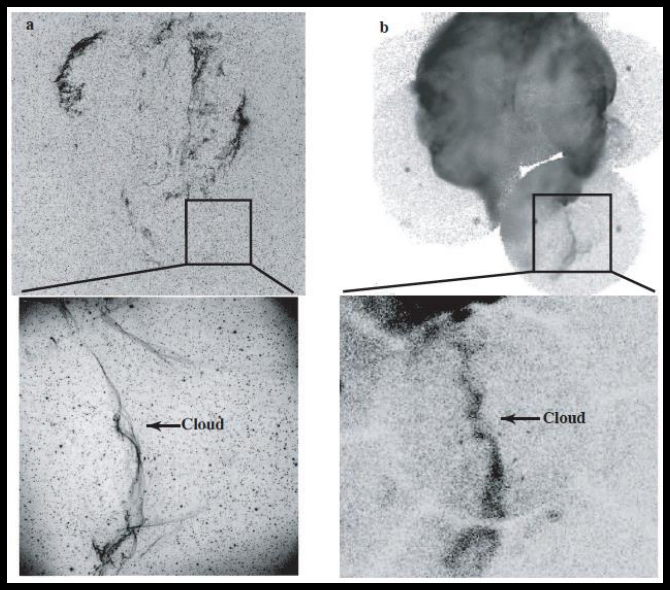
Velocities need to be a bit lower and densities much higher

This is consistent with what we see.

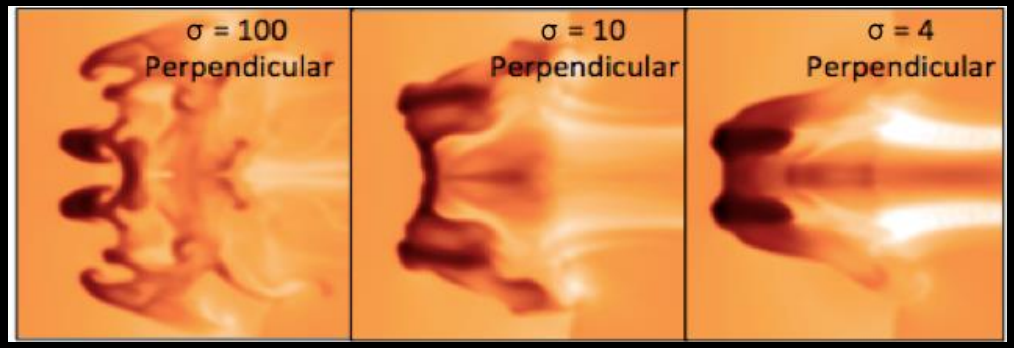
The field is strong enough to turn shocks into waves

Time-dependent models need to be done

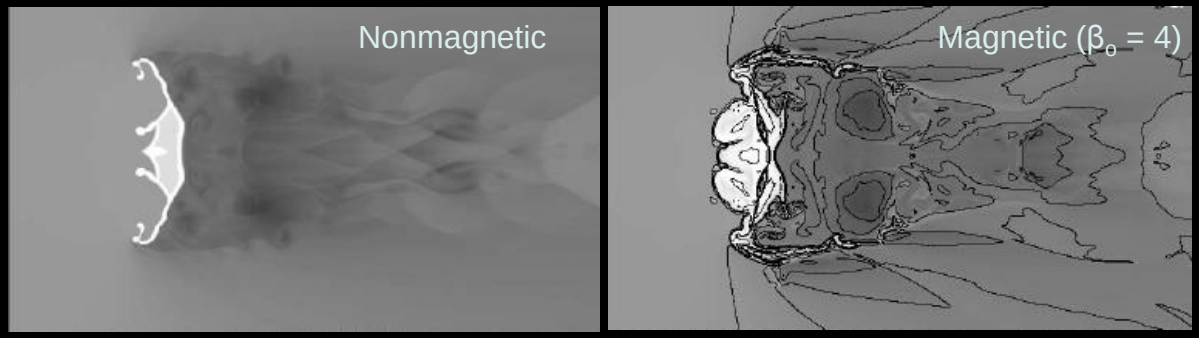
Shocked Magnetized Clouds



Patnaude and Fesen 2005 ApJ



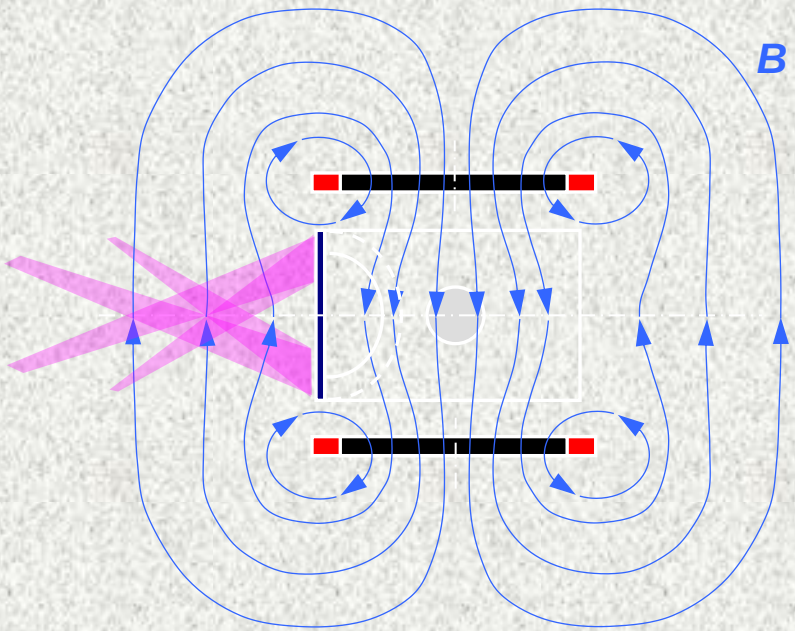
Effects of a Weak Magnetic Field on Shocked Cloud

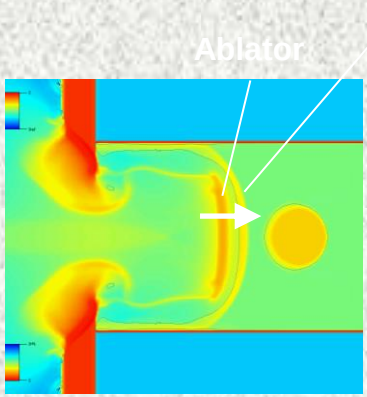


Fragile et al. 2005 ApJ

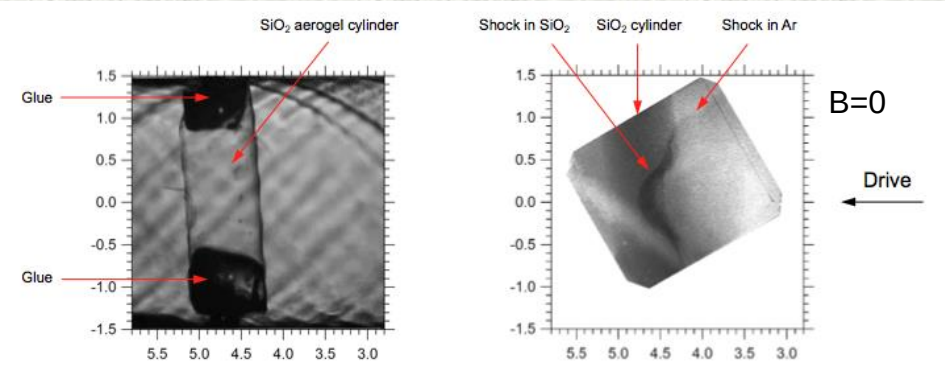
Experiments: Observe Stages of Breakup

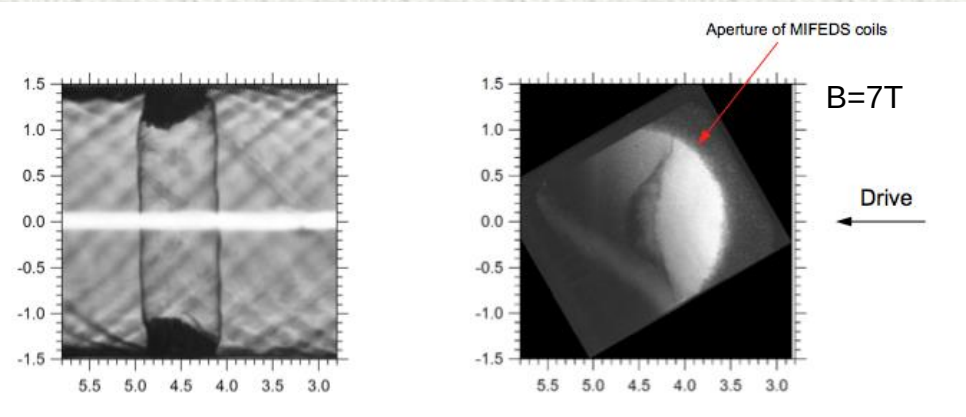
Foam Rod Experiment





Non-Magnetic Model





Concept: Magnetic Field inhibits instabilities in shock around obstacle

Details: 2 mg/cc Ar gas (preheated, to increase conductivity and magnetic-diffusion timescale) in thin-wall CH tube. 50 mg/cc SiO_2 aerogel rod

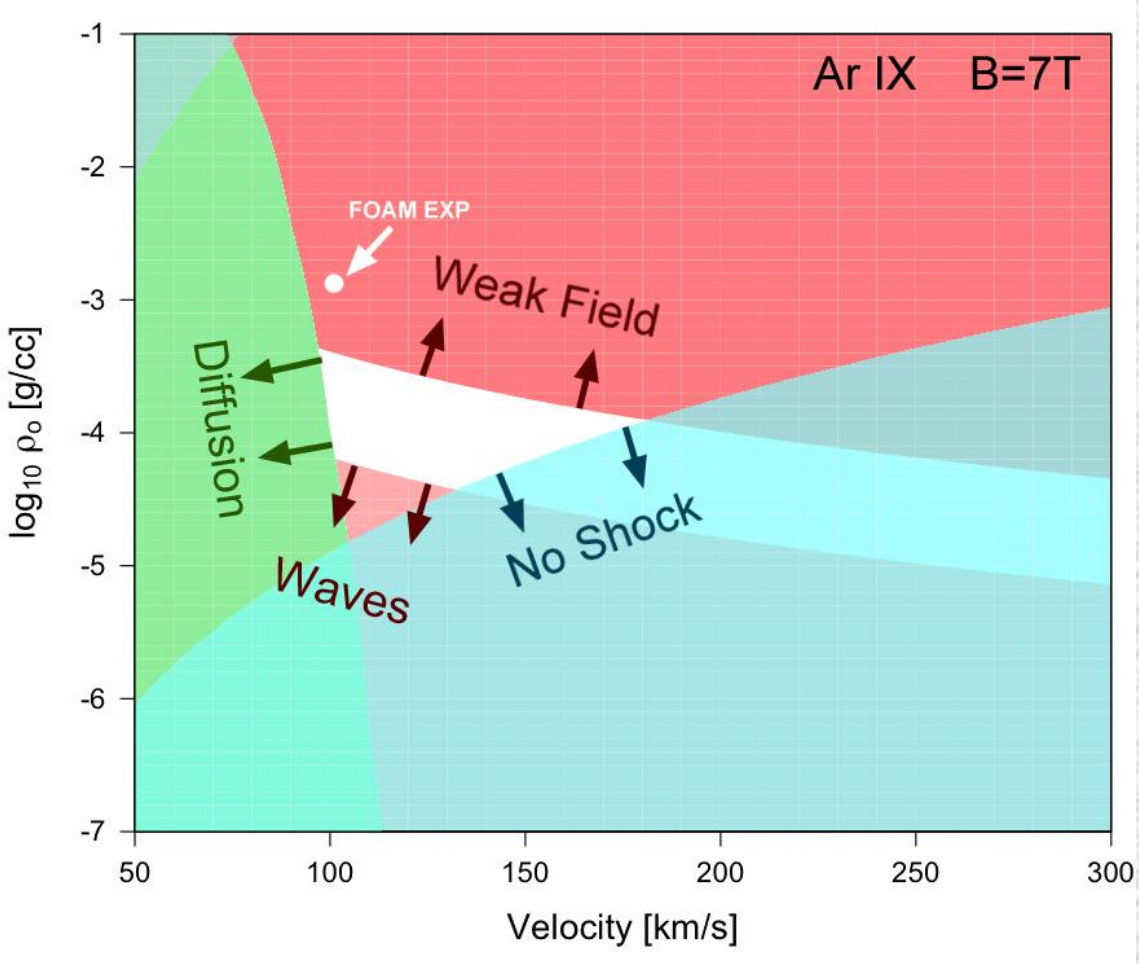
Foam Rod Experiment Explained

Parameters

- V = 100 km/s
- ρ = 1.6 mg/cc
- Ar, take to be Ne-like Ar IX (Z=8, A=40)
- B = 7 T

Experimental Results

Shock visible in Argon
No effect from Field



A shock should form

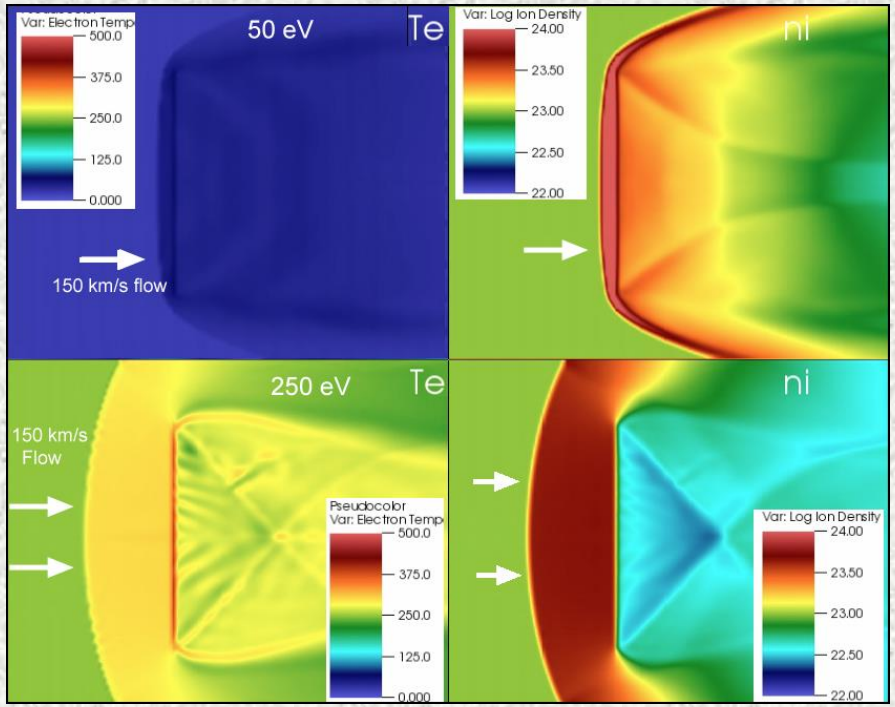
It should be a plasma

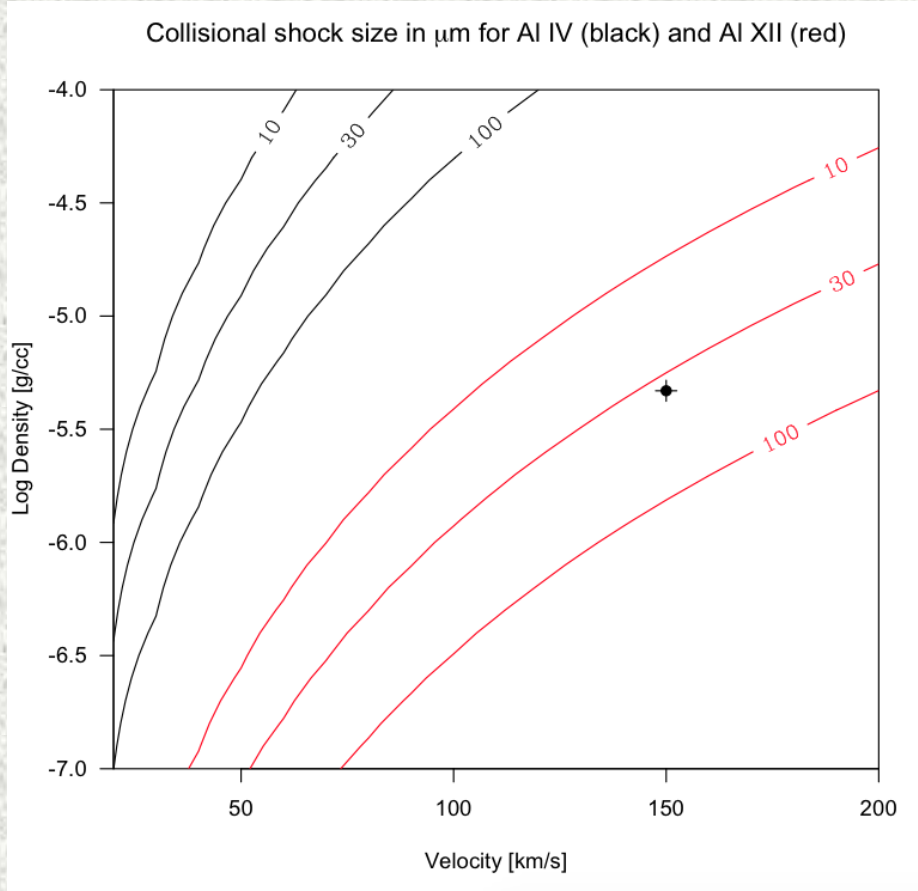
Magnetic Diffusion is a bit of a problem

But the B field is just too weak to see any dynamical effects

PERSEUS Models of 150 km/s Al flow onto a Slab

(P. Gourdain)





T (eV)	T(K)	Mach #	Cs (km/s)	Shock?
5	5.8e4	28	5.4	no
50	5.8e5	8.8	17	weak
250	2.9e6	3.9	38	yes

The numerical behavior makes sense. Increasing Z while keeping A (=27 for Al) fixed lowers the collisional size scale to smaller than the slab size and creates a shock

Moving Ahead

- The optimal parameter space to observe dynamical effects in magnetized laboratory shocks at Omega is rather narrow, but nonzero
- Both the wire and the accretion-column experiments seem reasonably close to their goals, but flows need to be less time-variable
- Optimally, a new design will have more steady velocities and densities with time so the drives looks more like a wind and less like a pulse
- If possible we should make everything larger. Making the wire 1mm helps a lot with diffusion and with shock size.
- Some preheating is a good idea to raise the C preshock ionization levels
- Longer-term, higher B (new instrumentation) will make a world of difference