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Basic scalings for collisionless shock experiments*

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OUTLINE

Collisionless shocks vs “standard” shocks

Scaling for the shock mediated by Weibel instability

Scaling for the shock mediated by electrostatic modes

Summary

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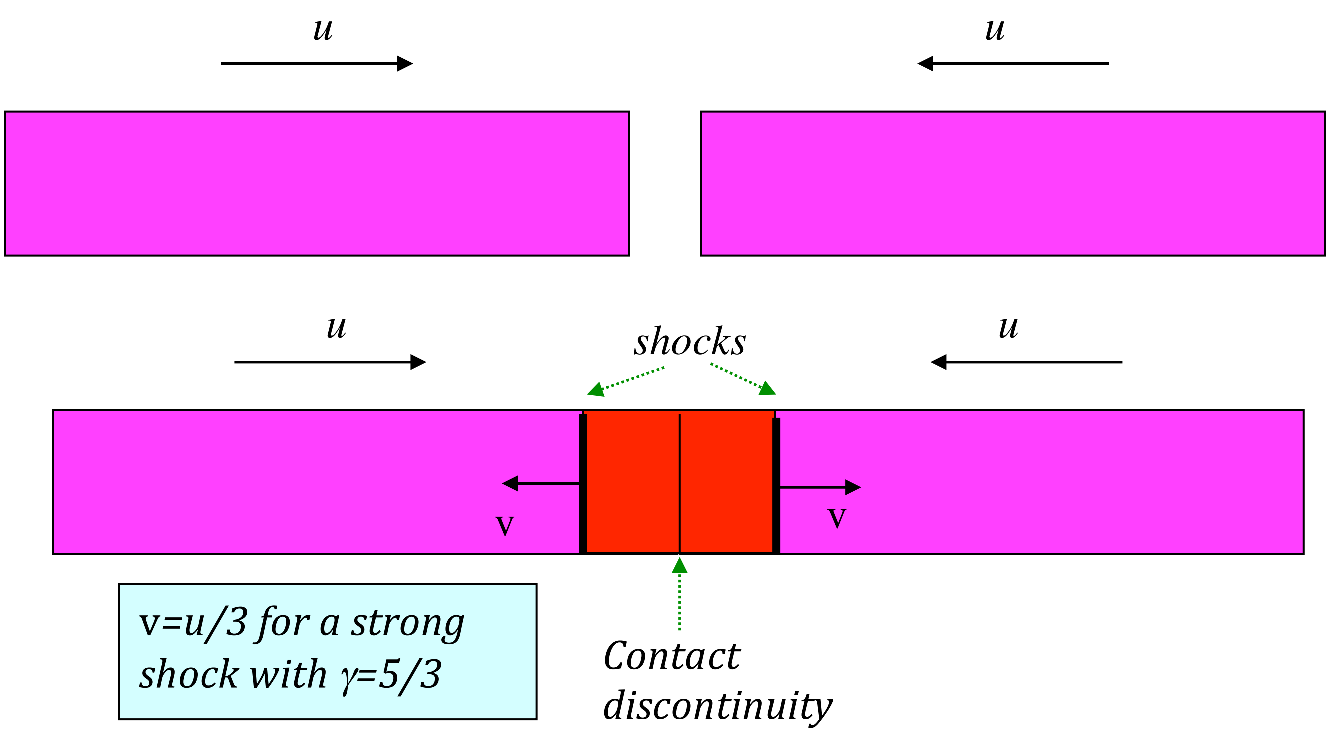
Summary

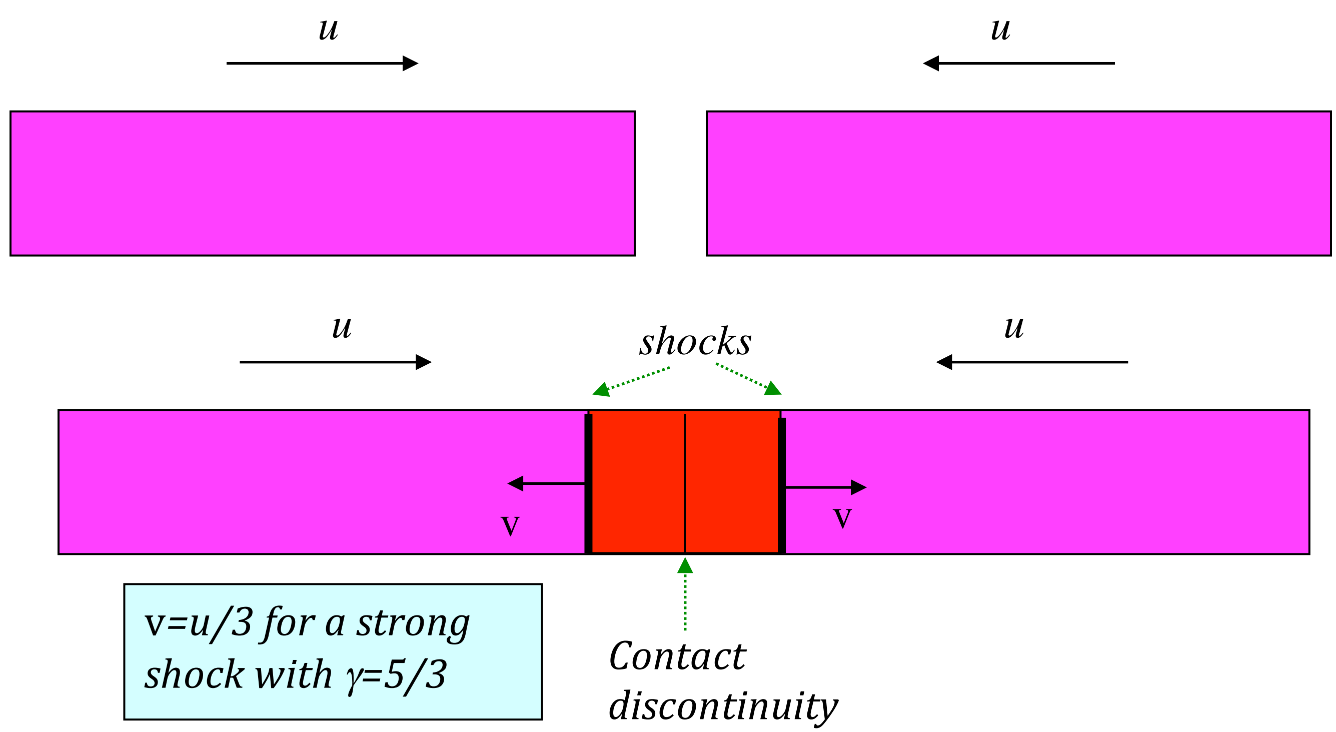
I consider only non-relativistic, initially un-magnetized plasmas (as in experiments of H.S. Park group)

“Standard” collisional shocks



v=*u*/3 *for a strong shock with* γ=5/3

“Standard” collisional shocks

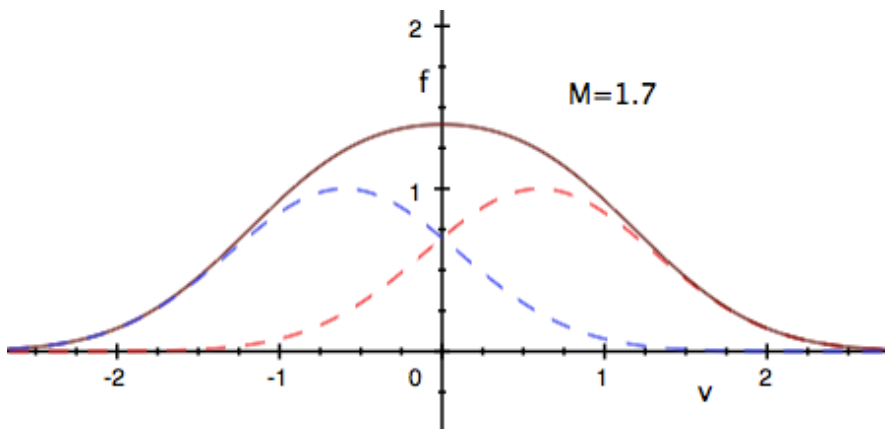


The presence of a “light” (electron) component may make the shock structure quite complex, and much wider than λ_{ii} (V.D. Shafranov, 1957)

Collisionless shocks are the shocks in which the particle scattering occurs on microturbulent electromagnetic fields driven by plasma instabilities

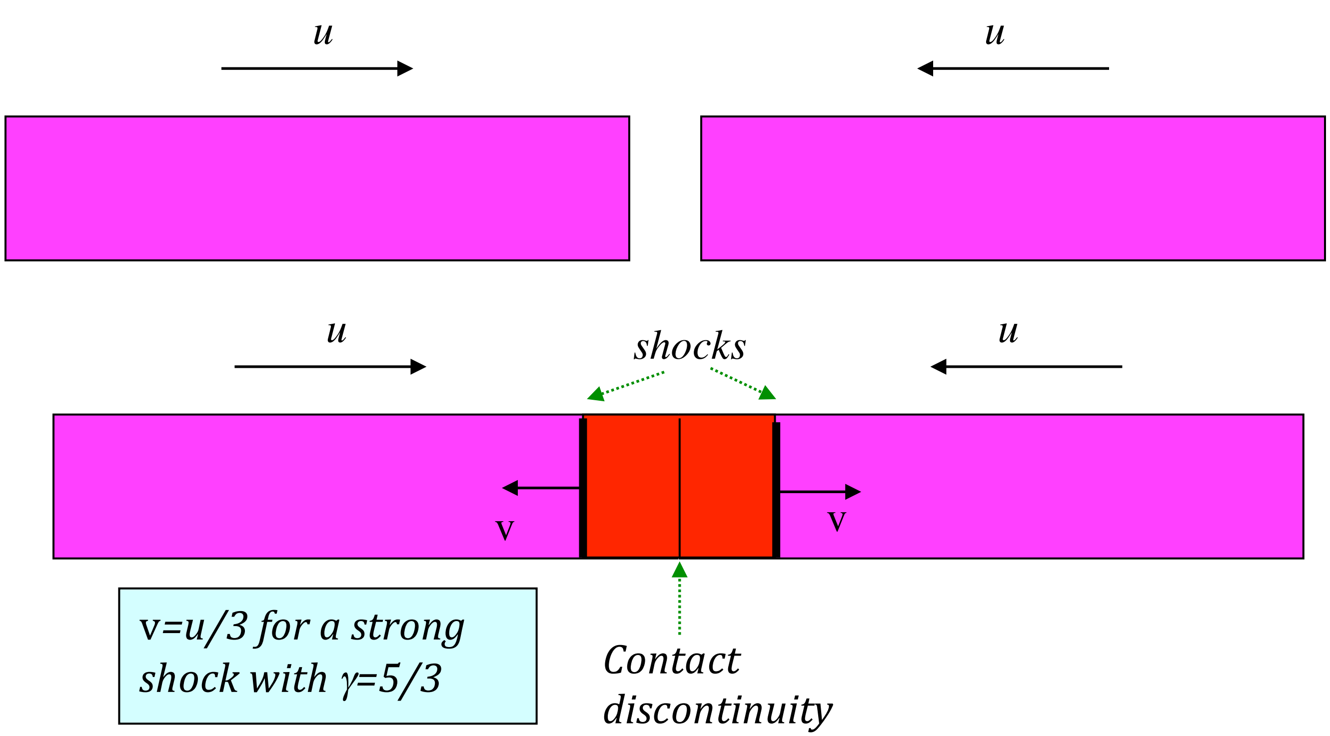
Plasma instabilities are caused by (significant) deviations from equilibrium distribution functions

An interesting question: how high should the relative velocity of two counter-streaming plasmas be in order to have the instabilities excited? [Can collisionless shocks exist at Mach number M of 1.1? 2?]



Note that "standard" shocks happily exist at M close to 1.

A great caution is needed in identifying the presence of collisionless shocks just by the density increase in the overlap region



Signatures of a strong-enough collisionless shock

Ion heating to “temperatures” approaching the kinetic energy of the flows

A weaker constraint: ion and electron heating to the “temperatures” significantly exceeding initial temperatures (and exceeding an always present collisional heating*)

* See poster #9

General scaling for the Maxwell-Vlasov description of the problem

$$\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \frac{\partial f_e}{\partial \boldsymbol{r}} - \frac{e}{m}\left(\boldsymbol{E} + \frac{\mathbf{v} \times \boldsymbol{B}}{c}\right) \cdot \frac{\partial f_e}{\partial \mathbf{v}} = 0$$

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \frac{\partial f_i}{\partial \boldsymbol{r}} - \frac{Ze}{Am_p}\left(\boldsymbol{E} + \frac{\mathbf{v} \times \boldsymbol{B}}{c}\right) \cdot \frac{\partial f_i}{\partial \mathbf{v}} = 0$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi e}{c}\left[-\int f_e \mathbf{v} d^3\mathbf{v} + Z\int f_i \mathbf{v} d^3\mathbf{v}\right]$$

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$$

Input parameters: electron density n_e, ion initial velocity u (negligibly small initial thermal spread of both electrons and ions), Z and A for the ions.

Introduce dimensionless variables:

$$t' = t/\tau; \quad \boldsymbol{r}' = \boldsymbol{r}/\ell; \quad \mathbf{v}' = \mathbf{v}/u; \quad \boldsymbol{B}' = \boldsymbol{B}/B_0 \quad \boldsymbol{E}' = \boldsymbol{E}/E_0$$

$$f_e' = \frac{u^3}{n_e} f_e; \quad f_i' = \frac{Zu^3}{n_e} f_i$$

Scaling units:

$$\tau = \frac{1}{\omega_{pe}} \frac{c}{u}; \quad \ell = \frac{c}{\omega_{pe}}; \quad B_0 = \frac{4\pi neu}{\omega_{pe}}; E_0 = \frac{4\pi neu^2}{\omega_{pe} c}$$

Obtain:

$$\frac{\partial f_e'}{\partial t'} + \mathbf{v}' \cdot \frac{\partial f_e'}{\partial \boldsymbol{r}'} - \left(\boldsymbol{E}' + \mathbf{v}' \times \boldsymbol{B}'\right) \cdot \frac{\partial f_e'}{\partial \mathbf{v}'} = 0 \qquad \nabla' \times \boldsymbol{B}' = \left[-\int f_e \mathbf{v}' d^3\mathbf{v}' + \int f_i \mathbf{v}' d^3\mathbf{v}'\right]$$

$$\frac{\partial f_i'}{\partial t'} + \mathbf{v}' \cdot \frac{\partial f_i'}{\partial \boldsymbol{r}'} - \mu\left(\boldsymbol{E}' + \mathbf{v}' \times \boldsymbol{B}'\right) \cdot \frac{\partial f_i'}{\partial \mathbf{v}'} = 0 \qquad \nabla' \times \boldsymbol{E}' = -\frac{\partial \boldsymbol{B}'}{\partial t} \qquad \mu = \frac{m_e}{m_p} \frac{Z}{A}$$

This means that the distances (characteristic wave-length, shock width) scale as

$$L = \frac{1}{\sqrt{n_e}} g_L(\mu),$$

where *g* is a universal function (the same for all systems). For almost all ion species $\mu=(1/2)m_e/m_p$; an exception is hydrogen.

Similarly, for the temporal scale *t** and other parameters, one has:

$$t^* = \frac{1}{u\sqrt{n_e}} g_t(\mu); \quad B = u\sqrt{n_e}\, g_B(\mu); \quad E = u^2\sqrt{n_e}\, g_E(\mu)$$

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It is hypothetized that

$$g_L(\mu) \sim 1/\sqrt{\mu}$$

In future cryogenic experiments it might be worthwhile to compare hydrogen vs deuterium

Assumptions: heating to the temperatures greatly exceeding initial $T_{i,e}$; the external dimensions are large-enough; no collisions

A role of collisions may be significant: intra-jet ion-ion collisions may be quite frequent

Our scaling provides a tool for assessing this process (switching from carbon to beryllium with the same n_e and u would change collisionality without changing anything else)

Analogous scalings can be developed for the electrostatic instability

$$L = \frac{u}{\sqrt{n_e}} h_L(\mu); \quad t^* = \frac{1}{\sqrt{n_e}} h_t(\mu); \quad \varphi = u^2 h_\varphi(\mu)$$

Comparing experimental results with these scalings, one can objectively assess a mutual role of the Weibel vs electrostatic instabilities

SUMMARY

There exist useful scaling relations that allow one to sort out a relative importance of various instabilities

They allow also for an objective assessment of possible role of intra-jet collisions

In future, comparative study of hydrogen vs deuterium could shed light on the μ dependence