

Turbulent instabilities in the interstellar medium

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Turbulent Mixing and Beyond

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Instabilities in astrophysics



Some examples:

- Classical hydrodynamic instabilities (RT/RM/KH, e.g. in supernova remnants).
 - Thin shell instability (Vishniac)
 - Radiative cooling instability
 - Continuum-force driven instability
 - Line-driven instability
 - Ionization front instabilities (D-type, shadowing)
 - Wardle instability (\Rightarrow slip-driven MHD instability)
 - MHD shear (Balbus-Hawley) instability of disks
 - Instability of self-gravitating discs
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Classical hydrodynamic instabilities



Classical hydrodynamic instabilities widespread in the ISM, e.g.

- RM: in supernova, jet, stellar wind or ionized bubble interactions with surrounding medium,
- RT: from injection of hot gas at base of stratified media, as in starbursts or radio galaxies
- KH: in shock/clump or wind/wind interactions

Reynolds et al. (2005) on effective Reynolds number of buoyant flows in radio galaxies – effective viscosity may be a significant fraction of Spitzer, despite B ?

Radiative cooling instabilities



Cooling curve for astrophysical plasmas goes through a number of unstable regimes.

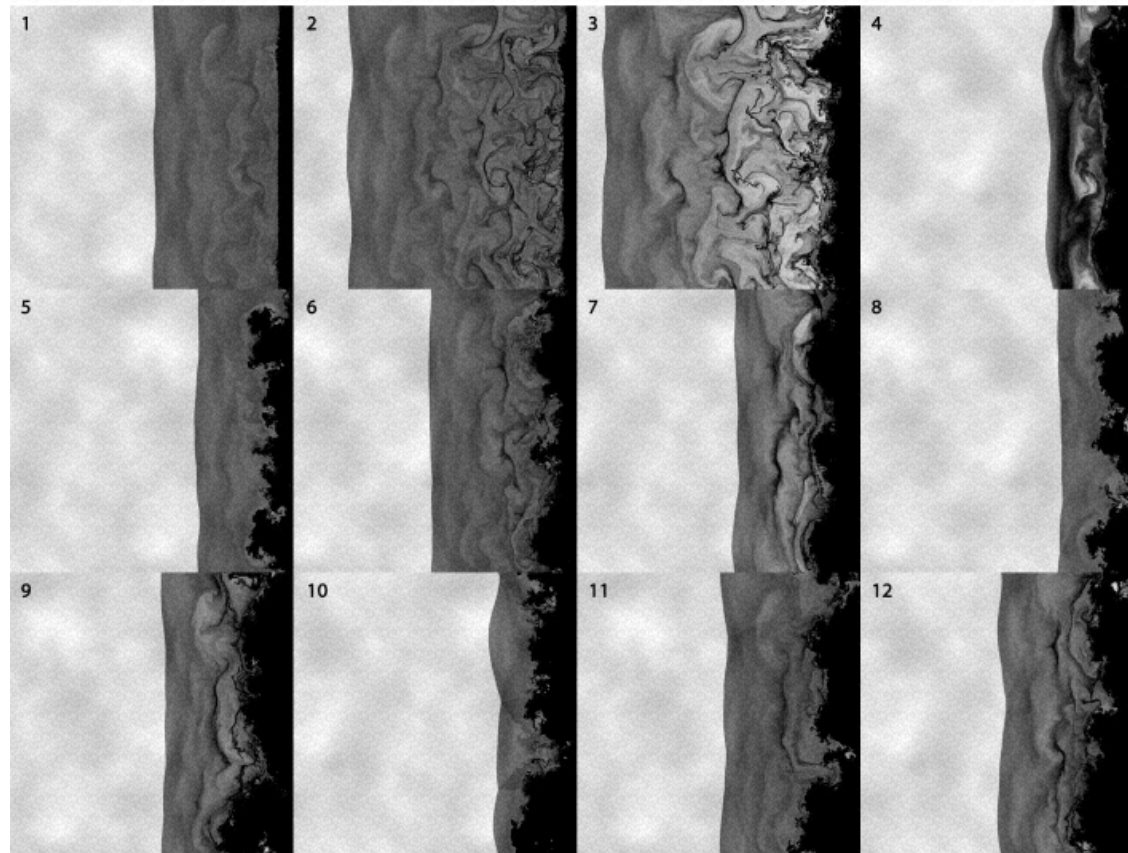
Shocks $v > 150 \text{ km s}^{-1}$ cool faster than the flow can respond \Rightarrow instability (Innes, Giddings & Falle.)

Numerical simulations in 1D show regular oscillations
In higher dimensions, find highly turbulent structures.

Radiative cooling simulations



Sutherland et al. (also Blondin, Hennebelle and others).



Thin shell instability



Ignoring likely thermal instability of cooling material, thin swept-up shells also subject to a particular form of Rayleigh-Taylor instability (Vishniac 1983).

Streams of heavy material escape from the driven side.

Reduced column density of the shell around these streams \Rightarrow enhanced acceleration, and instability growth.

Continuum-driven flow instability



Dominant emission processes often have emissivities $\propto n^2$.

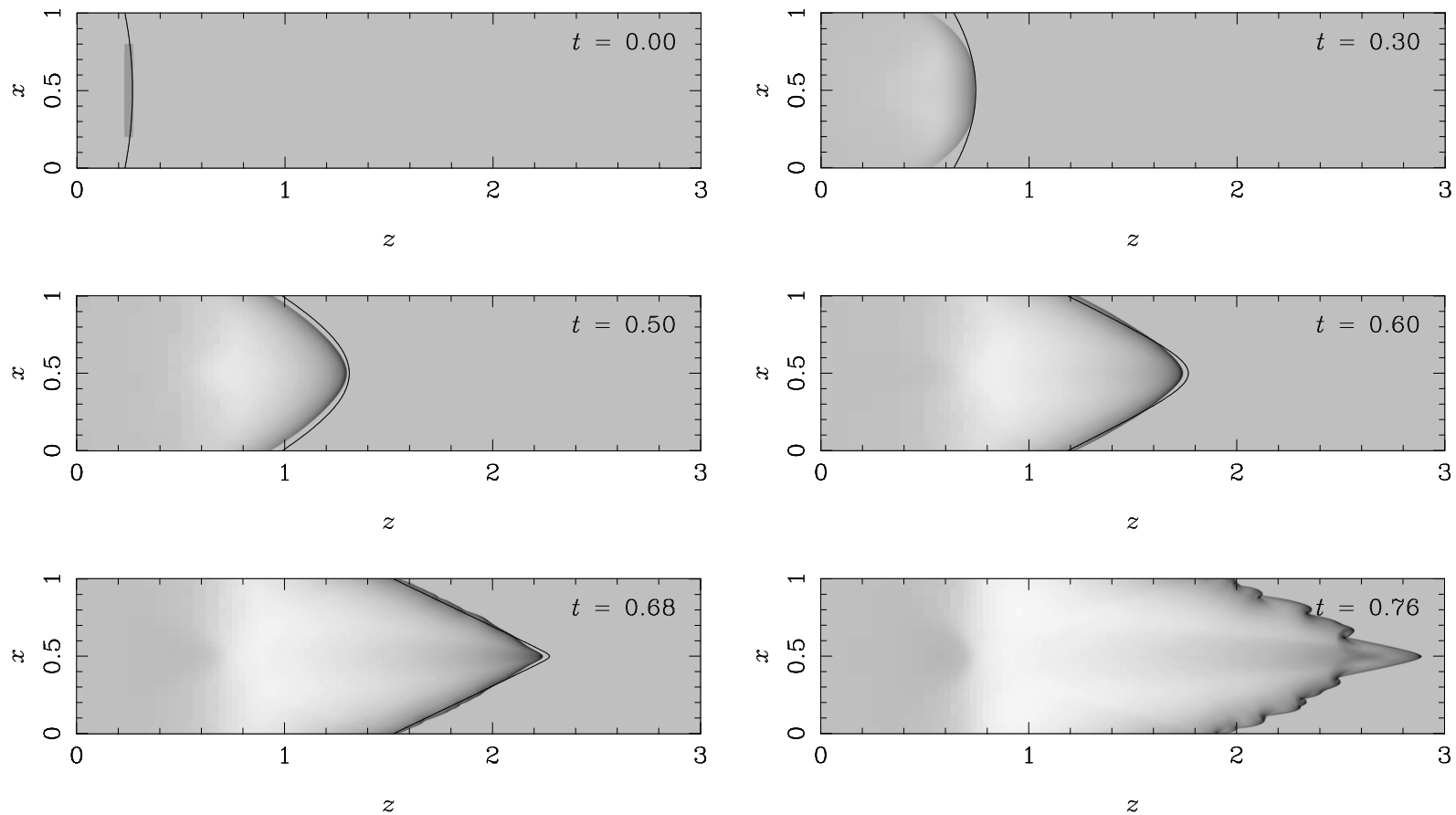
\Rightarrow absorption of radiation, and hence radiation force $\propto n^2$

Leads to instability growth, and the formation of radiation-driven shocks in plane parallel flow (Mestel, Moore & Perry)

Continuum-driven simulations



2D modelling (Williams 2000): thin structures are themselves unstable.



Continuum-driven discussion



Small perturbations tend to lead to the formation of radiation-driven darts.

As darts propagate, apex becomes progressively sharper. Confirmed by self-similar analysis.

In finite time, radius of curvature $\rightarrow 0$.

After this, leading edge breaks up into a random structure which spreads to fill the flow.

Behaviour has analogy to the Taylor-Green vortex flow.

Line-driven instability

- Hot star (O/B/WR) winds driven by radiation forces on the rich UV line spectrum (Castor, Abbott and Klein).
 - Sobolev approximation: force proportional to velocity gradient – determines how much stellar continuum local resonance lines can see.
 - If gas moves slightly faster than the smooth velocity gradient, the line driving force increases; if gas moves more slowly, the line driving force decreases \Rightarrow instability.
 - Classical spherically-symmetric models predict the formation of thin shells.
 - Simplified 2D modelling (Dessart & Owocki 2002, Gomez & Williams 2003) \Rightarrow while initial instability growth forms thin shells, these will soon break up into non-spherical structures.
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Ionization front instability



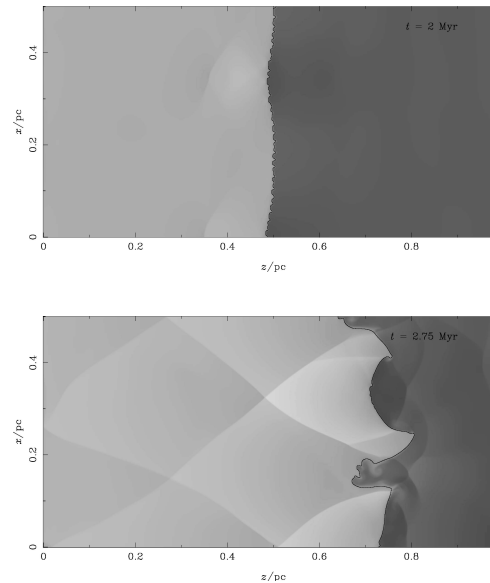
Astrophysical ionization fronts driven by UV radiation, e.g. from young stars or PN nuclei.

Front structures narrow, due to large absorption cross section in neutral gas.

Incident radiation field has to travel through ablated material and is absorbed by it

Variety of instability modes.

D-type Ionization front instability



D-type IF propagate more slowly than sound speed.

Takes time to flow through region significantly perturbed due to surface \Rightarrow delayed response \Rightarrow overstability.

Slow growth to nonlinearity (Vandervoort 1962; Sysoev 1997; Williams 2002).

Ionization front shadowing instability

Rapid transition from supersonic (R-type) to subsonic (D-type) motion. Also leads to instability (Garcia-Segura & Franco 1996; Williams 1999).

Transition when speed of IF is $\simeq 2\times$ sound speed in the ionized gas. This is speed \perp surface: ripples lead to regions of the front transitioning early, seeding turbulent flow.

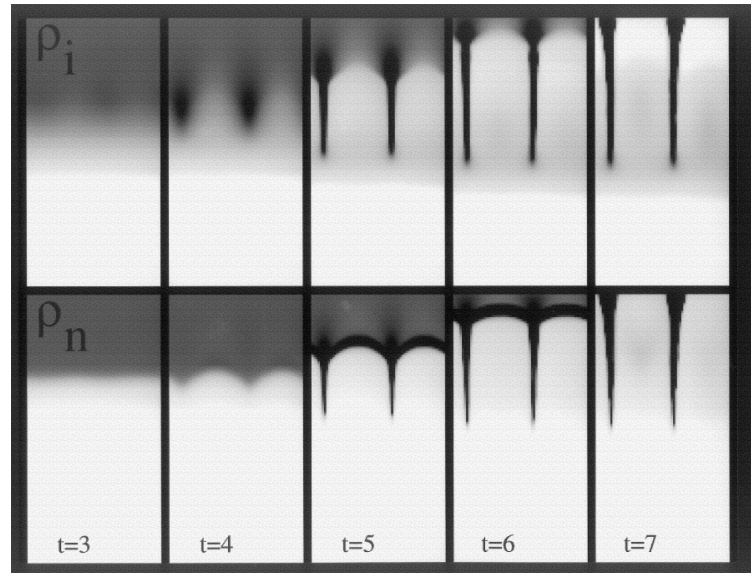
Enhanced by breaks in the dense shell of swept-up material allowing thin beams of ionizing radiation to escape.

Recently confirmed by detailed 3D calculations (Whalen & Norman 2008).

Slip-driven MHD instability



Multi-component flows are subject to a variety of instabilities.



One such instability was found by Wardle (1990) in multifluid MHD shocks (numerical results from Stone 1997)

Slip-driven MHD theory



- Tytarenko, Williams & Falle (2002) relate to general property of MHD flows, i.e. slow-mode propagation speed small in directions nearly $\perp B$.
 - Subcharacteristic criterion violated *wherever* one component of a multifluid flow satisfies the MHD equations, and there is finite slip.
 - Likely to be fundamental process underlying the Wardle instability.
 - Possibly a significant impact in other circumstances (e.g. the rate of ambipolar diffusion, i.e. MHD-driven fractionation, in molecular clouds).
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MHD shear instability of disks



In shearing disk flow, tiny initial seed magnetic fields will be stretched
 \Rightarrow in-plane instability (see Balbus & Hawley 1998 for a review).

Buoyant instability of resulting flux \Rightarrow instability spreads in the the vertical plane, in a similar fashion to coronal loops in the Sun.

Process may maintain the viscous transport necessary for accretion disk radiation in many systems (young stellar objects, symbiotic stars, active galactic nuclei).

Instability of self-gravitating discs



Self gravitating disks (e.g. in spiral galaxies) are locally unstable, depending on disk column density (e.g., Binney & Tremaine).

Velocity dispersion in such galaxies is *observed* to have

$$Q = \frac{\sigma \kappa}{3.36 G \Sigma} \sim 2 \quad (1)$$

where Q is known as the Toomre stability parameter.

σ is local velocity dispersion; κ is epicycle frequency and Σ is column density.

Conclusions

- Parker suggests that in general in astrophysics, magnetism leads to instability.
- More generally, this overview suggests that *almost any* local source of free energy \Rightarrow instability \Rightarrow turbulence.
- Nonlinear saturation: turbulence grows to dynamical equilibrium where random motions are sufficient to suppress instability growth.
- However the character of astrophysically observed 'turbulence' (i.e. unresolved line-of-sight velocities projected on the sky) may be very different from terrestrial fluid experiments.