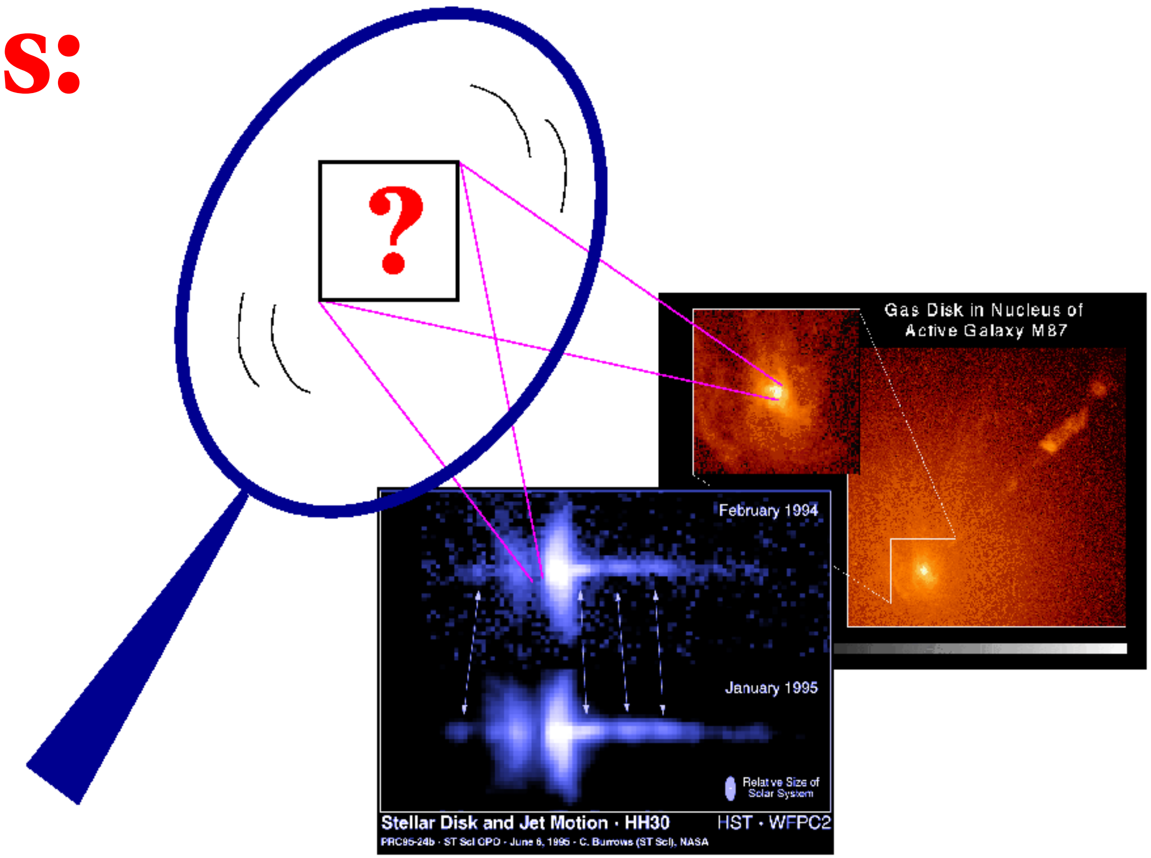
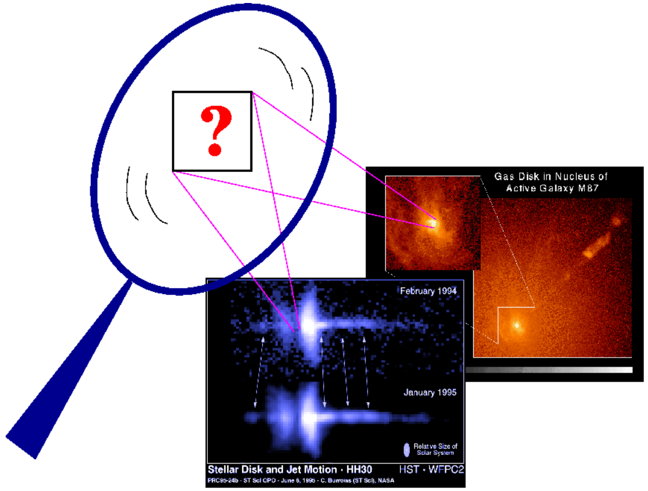
Outflows & Jets: Theory & Observations



Lecture winter term 2008/2009

Henrik Beuther & Christian Fendt

Outflows & Jets: Theory & Observations

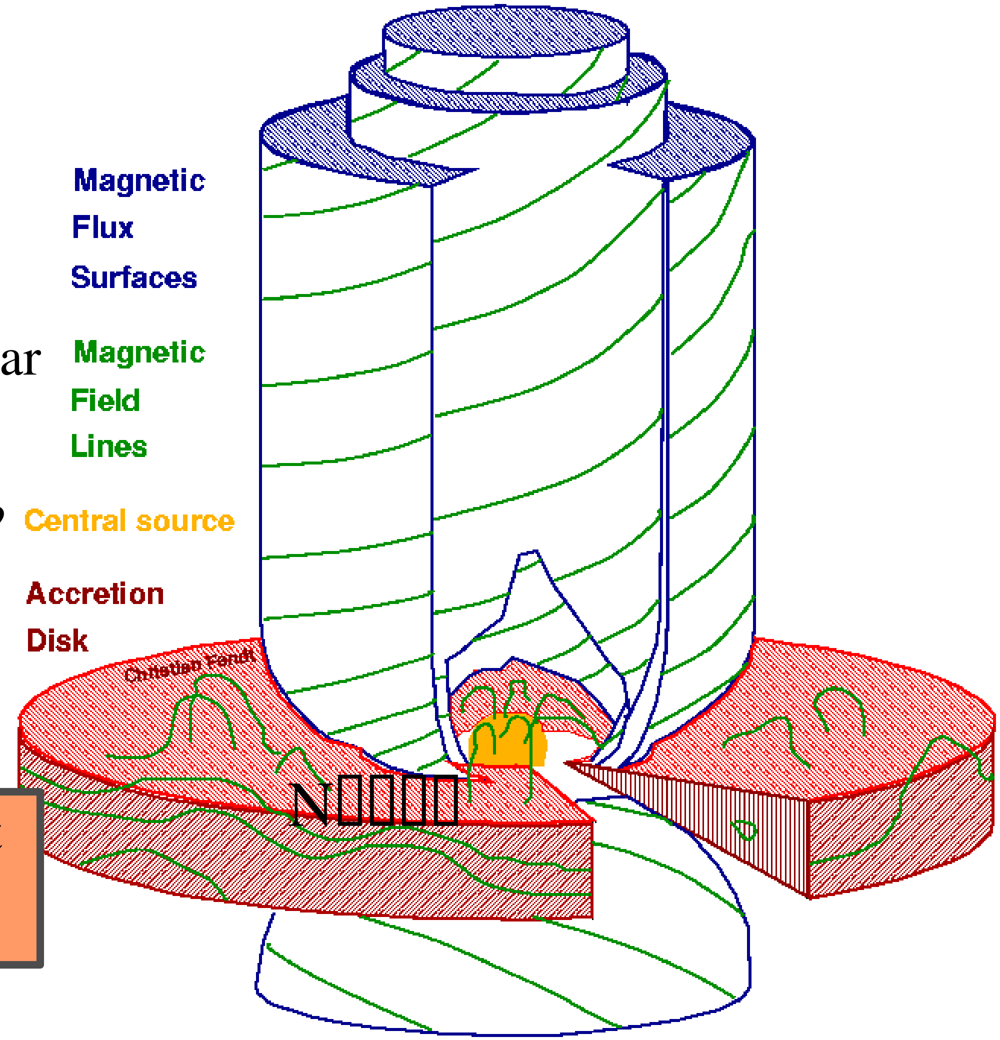


10.10 Introduction & Overview ("H.B." & C.F.)
17.10 Definitions, parameters, basic observations (H.B.)
24.10 Basic theoretical concepts & models I (C.F.): Astrophysical models, MHD
31.10 Basic theoretical concepts & models II (C.F.) : MHD, derivations, applications
07.11 Observational properties of accretion disks (H.B.)
14.11 Accretion, accretion disk theory and jet launching (C.F.)
21.11 Outflow-disk connection, outflow entrainment (H.B.)
28.11 Outflow-ISM interaction, outflow chemistry (H.B.)
05.12 Theory of outflow interactions; Instabilities (C.F.)
12.12 Outflows from massive star-forming regions (H.B.)
19.12 Radiation processes - 1 (C.F.)
26.12 and 02.01 Christmas and New Year's break
09.01 Radiation processes - 2 (H.B.)
16.01 Observations of AGN jets (C.F.)
23.01 Some aspects of AGN jet theory (C.F.)
30.01 Summary, Outlook, Questions (H.B. & C.F.)

Standard model of jet formation

-> 5 basic questions of jet theory:

- collimation & acceleration of a disk/ stellar wind into a jet ?
- ejection of disk/stellar material into wind?
- accretion disk structure?
- generation of magnetic field?
- jet propagation / interaction with ambient medium



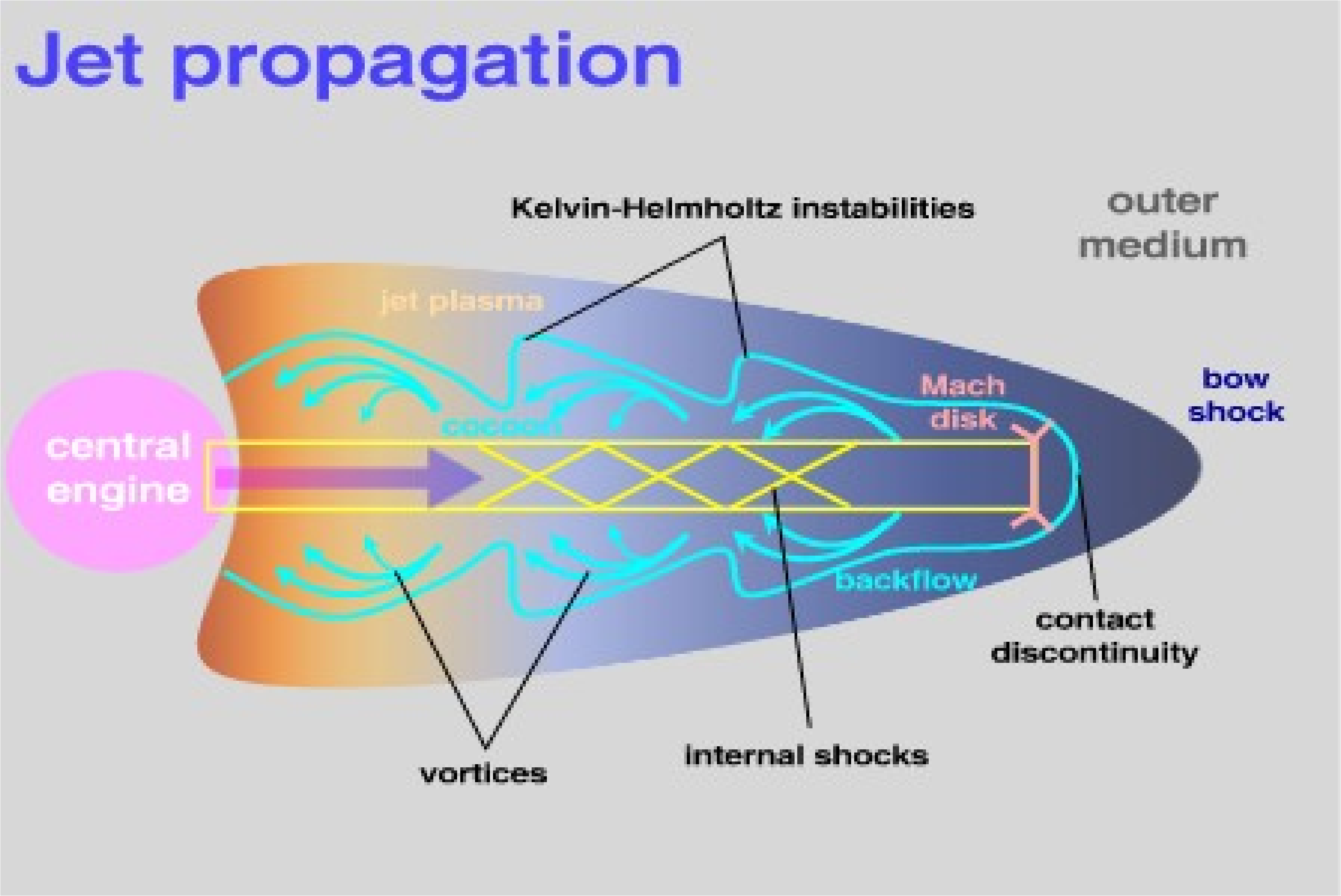
Topics today:

- molecular outflows
- jet instabilities
- shocks (HD, MHD)

Standard model of jet formation

- jet propagation / interaction with ambient medium

Topics today: **molecular outflows, jet instabilities, shocks (HD, MHD)**



Driving of molecular outflows

Molecular outflows are "momentum-driven" ...

-> momentum-driven: excess energy is radiated away
-> energy-driven: energy adiabatically converted into kinetic energy

-> observational constraints:

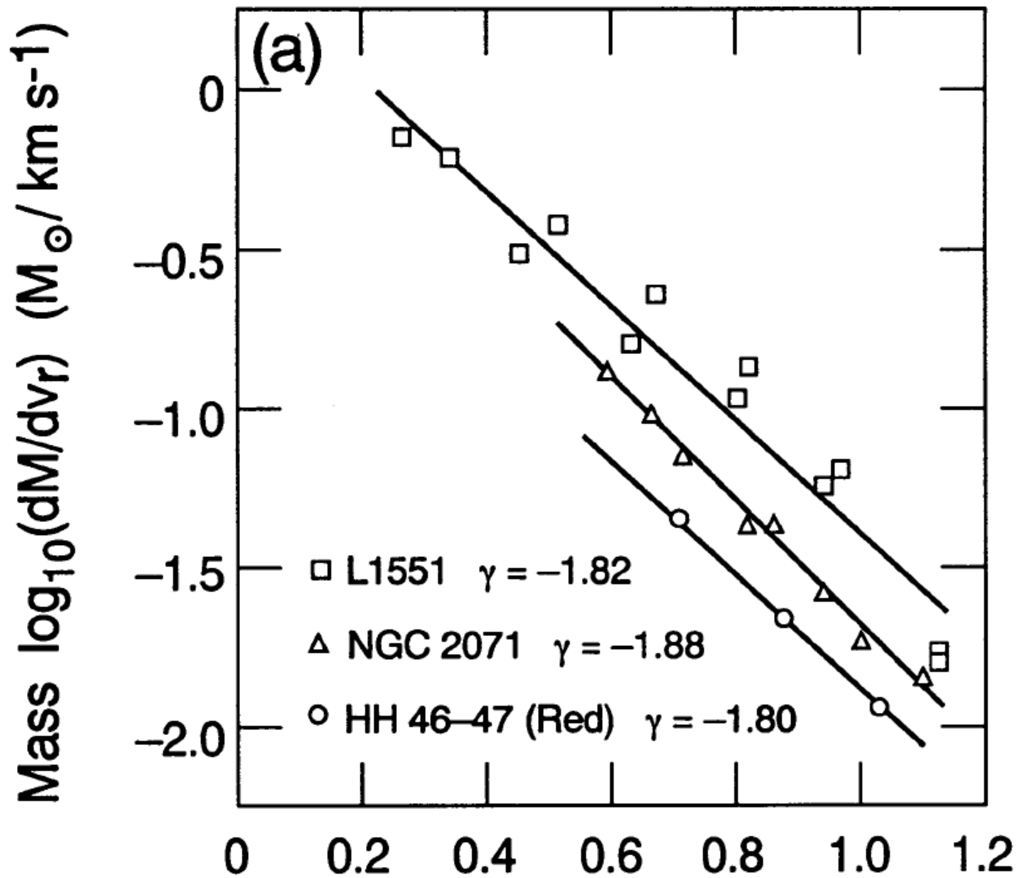
1) M-V relation (v_j fiducial jet speed):

$$\frac{dM(v)}{dv} = k\left(\frac{v}{v_j}\right)^{-\gamma}$$

2) increasing velocity (~ linear) with distance, "acceleration": "Hubble law" (Lada & Fich 96)

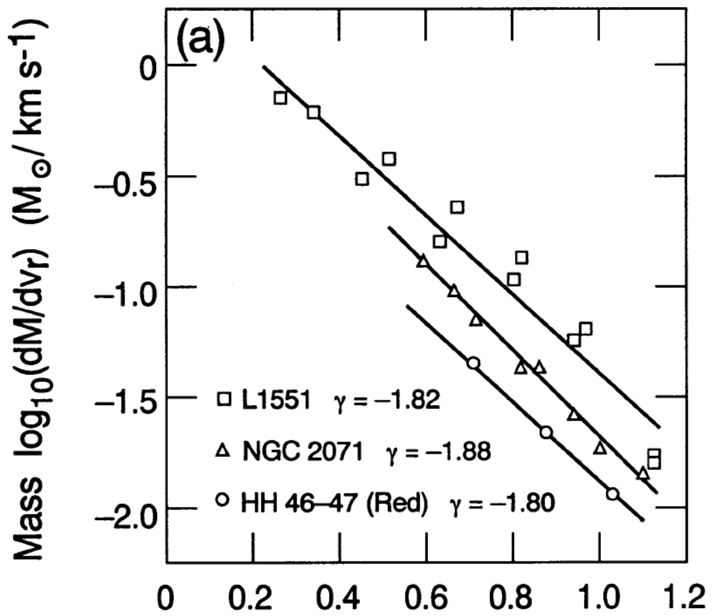
-> defines dynamical time scale:

$$t_{dyn} = r/\overline{v}$$



Radial velocity log10 (vr-v0) (km/s): (absolute radial velocity minus velocity at line center)

Driving of molecular outflows



Molecular outflows are "momentum-driven" ...

From observed M-V relation:

-> kinetic luminosity:

$$L_{kin} = \frac{1}{t_{dyn}} \int_{u_o}^{\infty} du\, u^2\, dM/du$$

-> momentum flow ("force"):

$$F_{out} = \frac{1}{t_{dyn}} \int_{u_o}^{\infty} du\, u\, dM/du$$

-> driver cannot be radiation of central star:

$$F_{out} = 10^{-3} M_o\, km/s/yr \gg L_{bol}/c$$

-> additional source for energy / momentum: **magnetic field** (via jet)

Driving of molecular outflows

Molecular outflows are “momentum-driven”

-> 4 model scenario of molecular flow acceleration (see Henrik's lecture):
jet entrainment, bow shock, wide angle wind, circulation model

-> main **questions to be answered by theory** (see Downes & Ray 1999):

- -> how much momentum is transferred to the ambient molecules?
- -> is there a power-law relation between the mass in the molecular flow and velocity?
- -> what are the proper motions of the molecular 'knots'?
- -> how does the knot emission behave in time?
- -> is the so-called Hubble law of molecular outflows reproduced?
- -> is there extra entrainment of ambient gas along the jet due to velocity variations (i.e. jet pulses) ?

-> answers are not yet known .... preference for jet-driven models

Driving of molecular outflows

Molecular outflows are "momentum-driven"

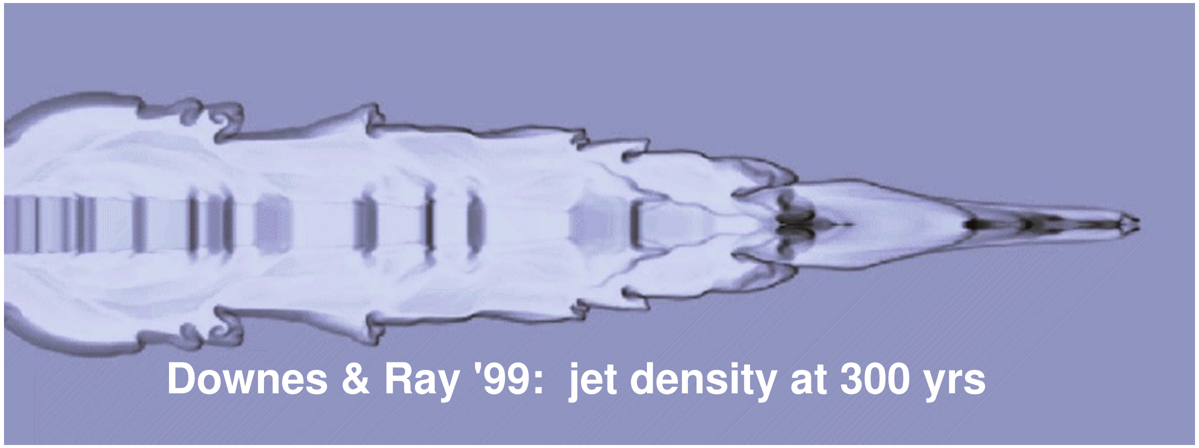
-> main **questions to be answered by theory** (see Downes & Ray 1999)

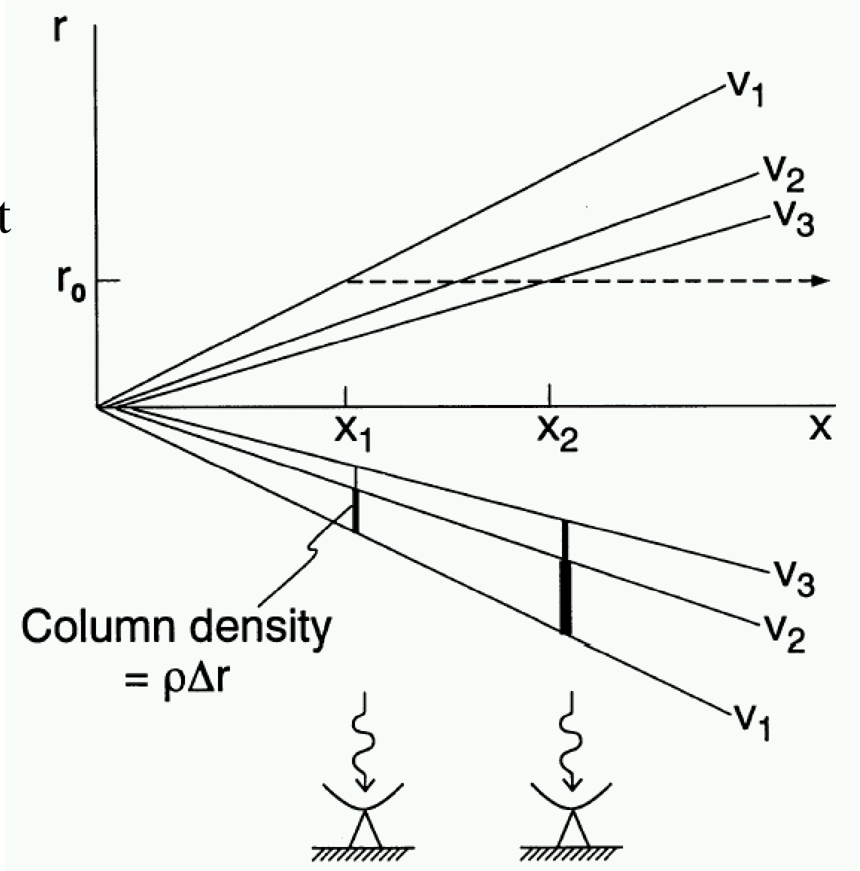
-> answers are not yet known .... preference for jet-driven models

-> indication that Hubble law is apparent effect:

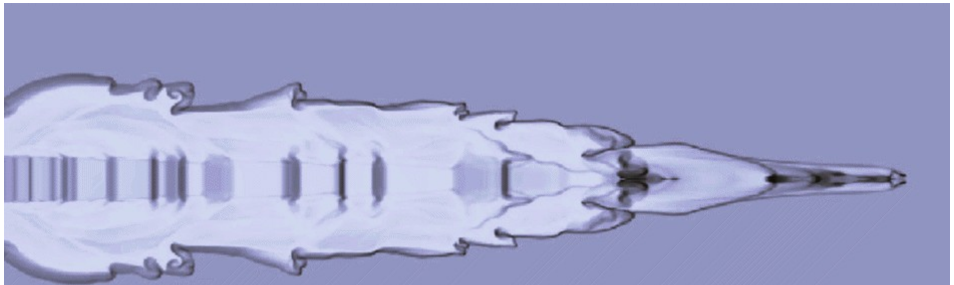
1) l. o. s . column density increases (Stahler 94) along turbulent outflow; v3 > v2 > v1; opt. thin -> high velocities become "visible" further out

2) projected bow shock velocity distribution (Downes & Ray 99)





Driving of molecular outflows



Downes & Ray '99: jet density at 300 yrs

Jet-driven molecular outflows

Numerical simulations (Downes & Ray 1999)

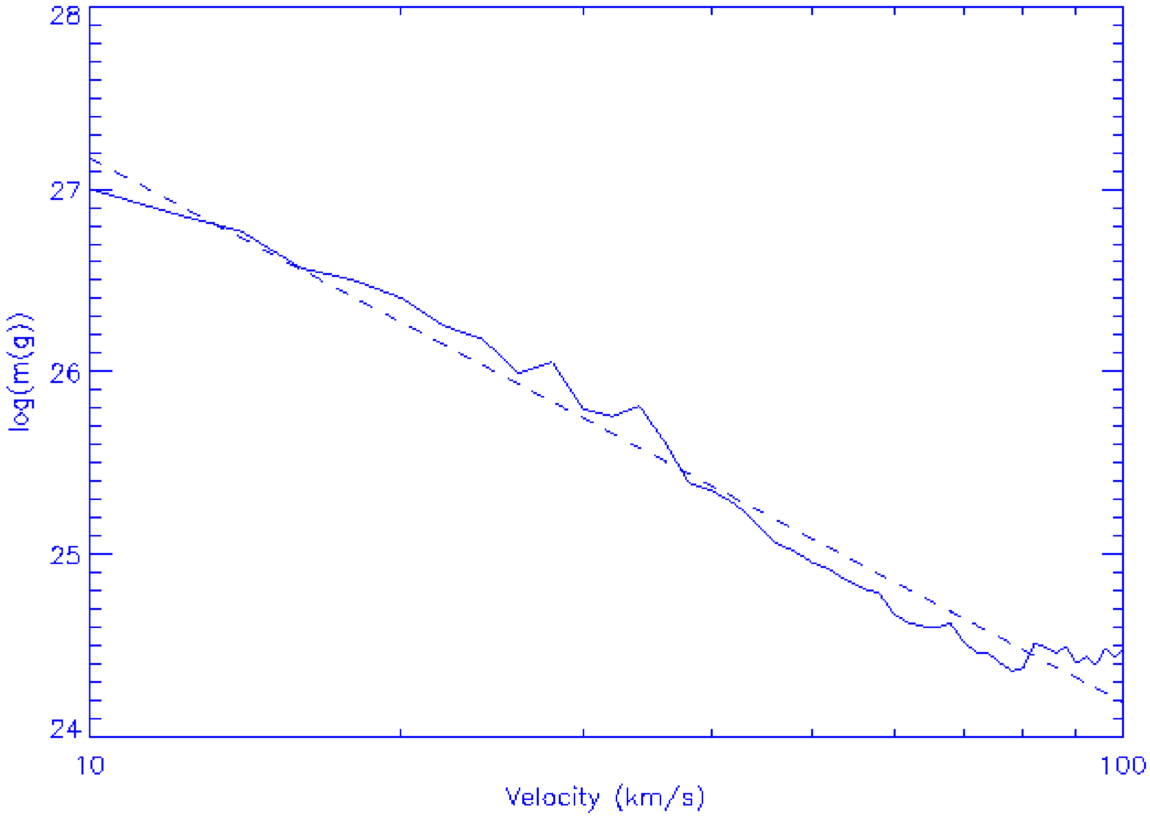
-> tricky: accelerate molecules without dissociating them -> proper cooling function ...

-> measure momentum transfer:

- momentum in molecules / total momentum in box ~ 0.1 .. 0.4
- inefficient momentum transfer for molecules, particularly for increasing density
- jet cooling narrows the jet head thus the cross section thus reduces momentum transfer

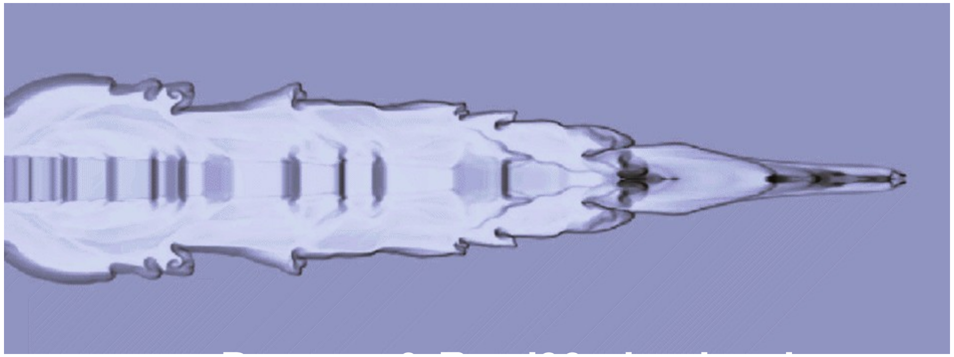
-> **power-law mass-veocity**

relation reporduced $\gamma = 2 - 4$



mass-velocity relation
(300 yrs, i= 60°)

Driving of molecular outflows



Jet-driven molecular outflows

Numerical simulations (e.g. Downes & Ray 1999)

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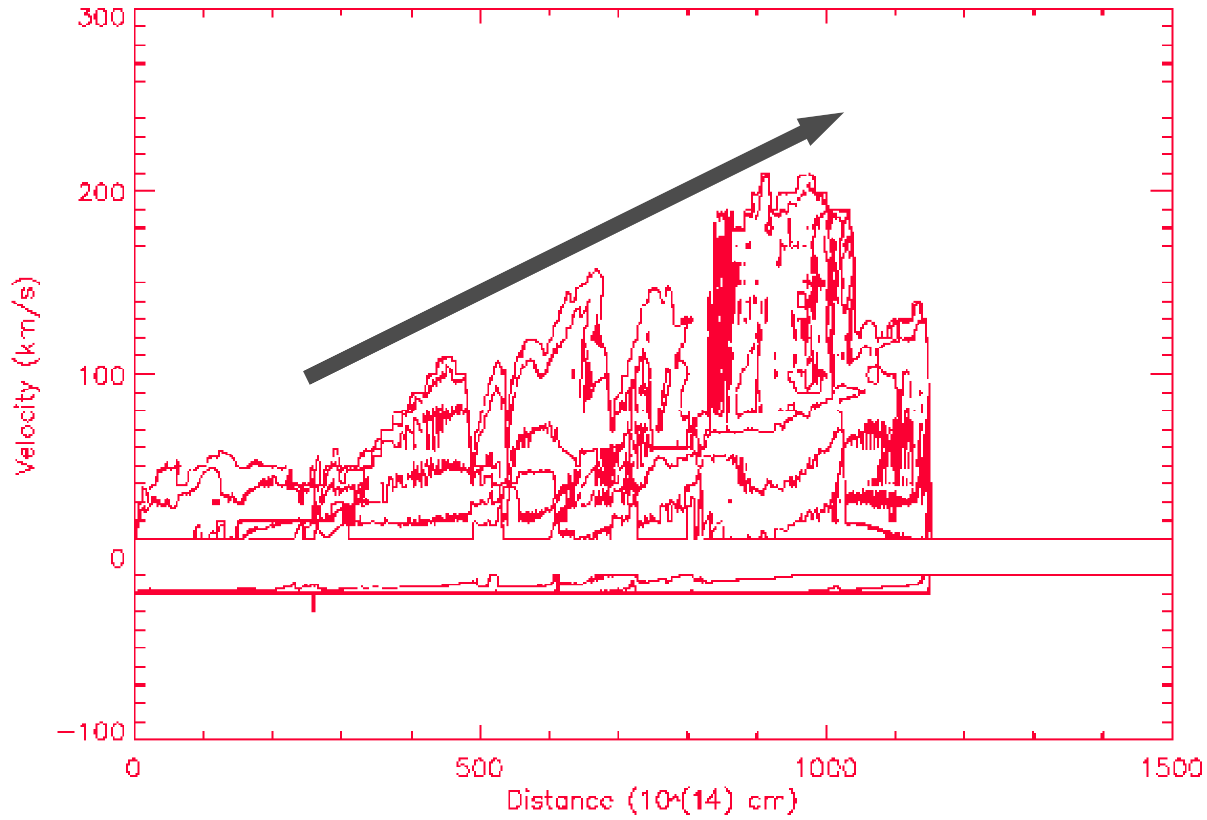
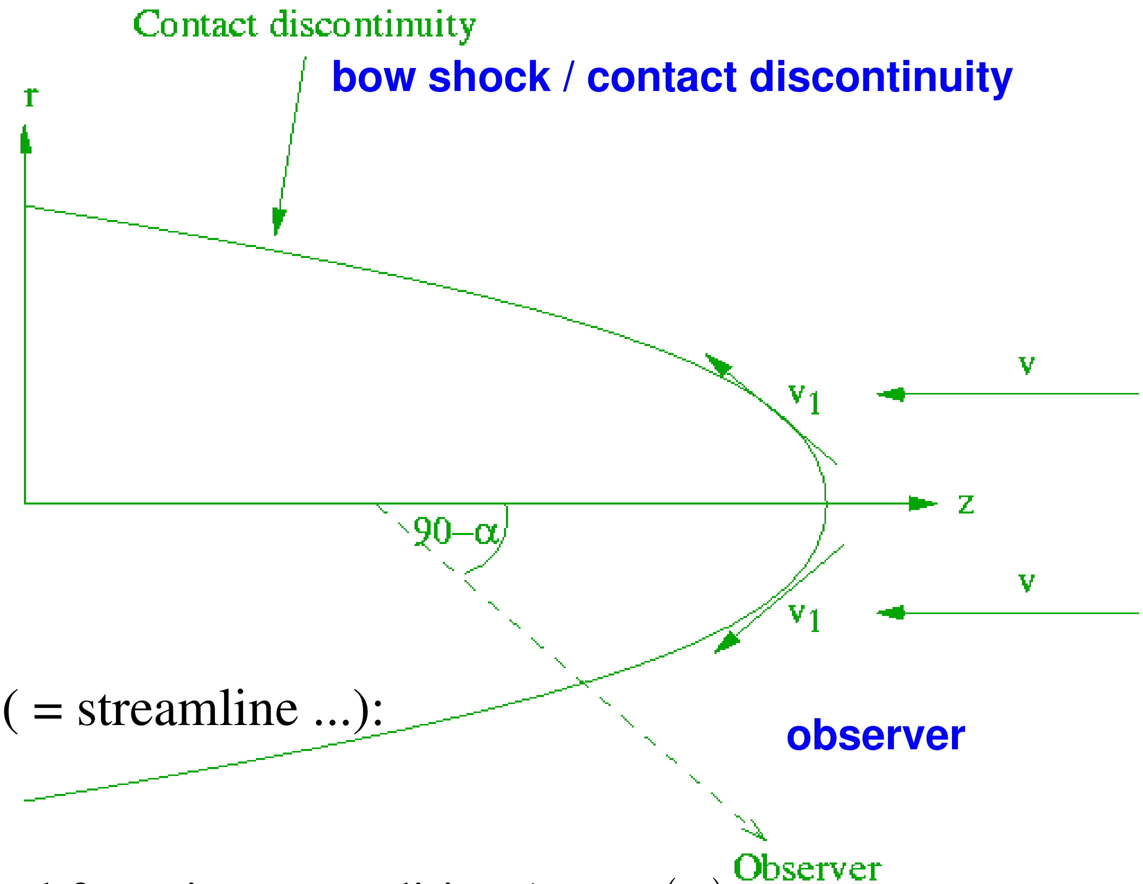
-> **Hubble law reproduced**



Hubble law
(300 yrs, i= 60°)

Driving of molecular outflows



Jet-driven molecular outflows

Analytical model for Hubble law
(Downes & Ray 1999)

Idealized bow shock:

-> shape $z = a - r^s\ ;\quad s \geq 2$
('a' is apex position of bow shock)

-> velocity ratio along the bow shock (= streamline ...):

$$\Re \equiv -v_z / v_r = s\left(a - z\right)^{\frac{s-1}{s}}$$

-> postshock velocity (would be derived from jump conditions): $v_1(z)$

-> radial component: $v_r(z) = \dfrac{v_1}{\sqrt{1+\Re^2}}$

-> component along line of sight: $v_{los}(z) = \dfrac{v_1}{\sqrt{1+\Re^2}}\left(\cos\alpha + \Re \sin\alpha\right)$

-> for strong shock, compression ratio of 4: $v_{los}(z) = v \cos\left(\arctan \Re\right)\sqrt{\dfrac{1}{16} + \Re^2}$

-> this implies Hubble-like position-velocity diagram

-> Hubble law is (partly) artifact of geometric

Instabilities in jet flows

Primer on jet instabilities

-> "instability": fluid system is unstable if small perturbations grow unbounded

- -> instabilities usually investigated from equilibrium state
- -> instabilities may lead to disruption of entire flow

-> jets propagation is affected by a number of instabilities

- -> Kelvin-Helmholtz-i., current driven i., sausage i., kink i. ...
- -> magnetic field may stabilise some instability modes (e.g. KHI)
- -> magnetic field may cause additional instabilities ("current driven")

-> in summary, real jets are surprisingly stable:

protostellar jets: jet length (sevaral pc) ~ 100 jet radii (< 100 AU)

AGN jets : jet length (several Mpc) ~ 100 jet radii (on kpc scale)

-> stability analysis: dispersion relation between angular frequency of perturbation and wave vector by wave ansatz:

$$D(\omega, \boldsymbol{k}) = 0 \quad ; \quad V \rightarrow V + V' \quad ; \quad V' \simeq \exp\left(i\left(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t\right)\right)$$

- -> stability is inferred from roots of dispersion relation; solution $\boldsymbol{k}$(w)
- -> roots with negative imaginary part of k correspond to spatially growing perturbations in some direction

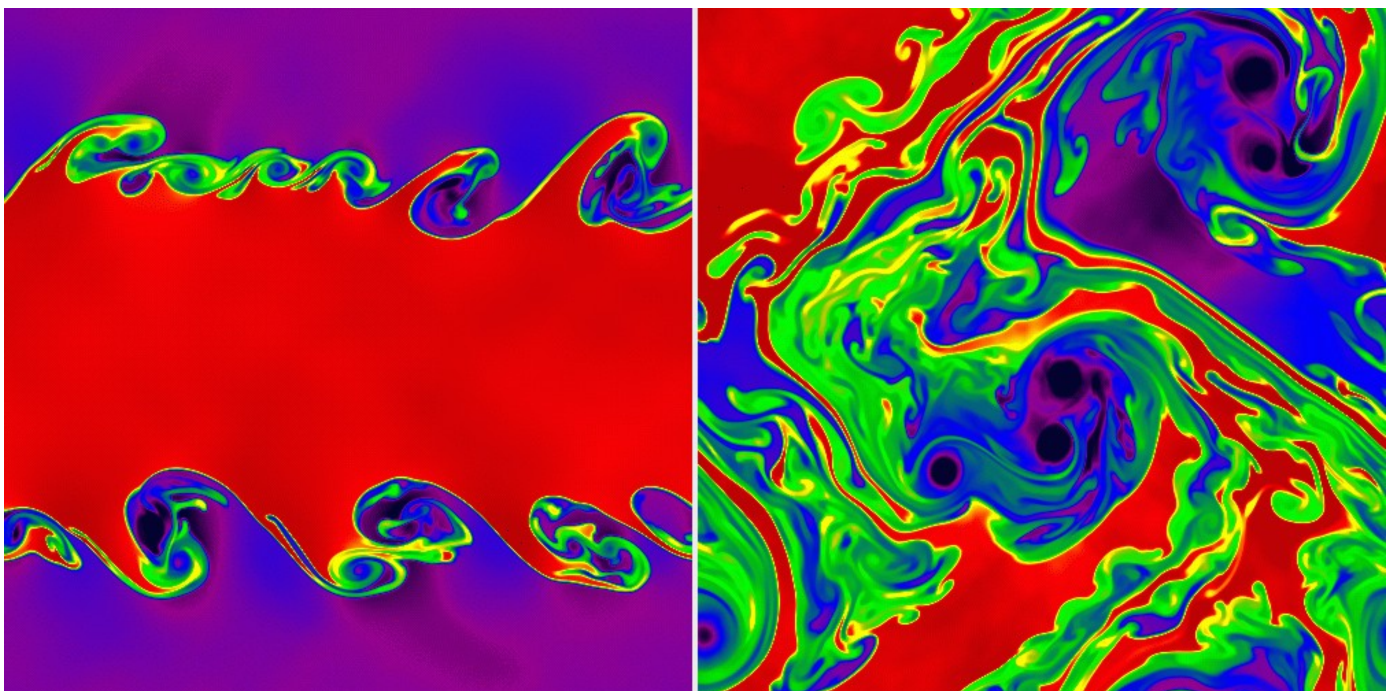
Instabilities in jet flows

Kelvin Helmholtz instability (KHI)

-> fluid layers, velocity shear -> growth of initial undulation
growth mechanism: centrifugal force due to flow along curved interface (see Shu 1992)

-> mathematical approach: (M)HD equations, linear perturbance, wave ansatz -> instability if relative Mach number of two streams $M^2 \cos^2\phi < 8$

-> numerical simulations to investigate nonlinear regime of instability



J. Stone et al; see www.astro.princeton.edu/~jstone/tests/kh/kh.html

Hydrodynamic simulation; time steps 1.0, 5.0; box of 512 x 512 cells; density 0.9 ...2.1

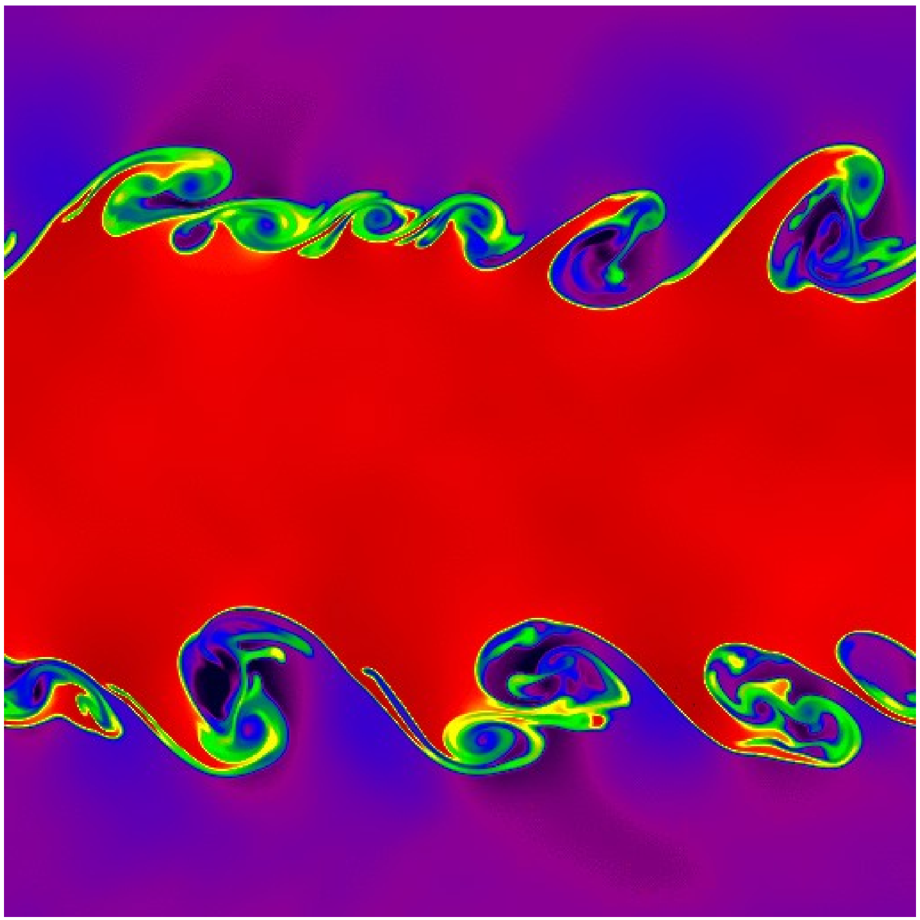
[vx]_1 = -0.5 ; **[vx]_2** = 0.5 ; ρ_1 = 1; ρ_2 = 2, P_1 = P_2; M_1 = 0.38, M_2 = 0.27

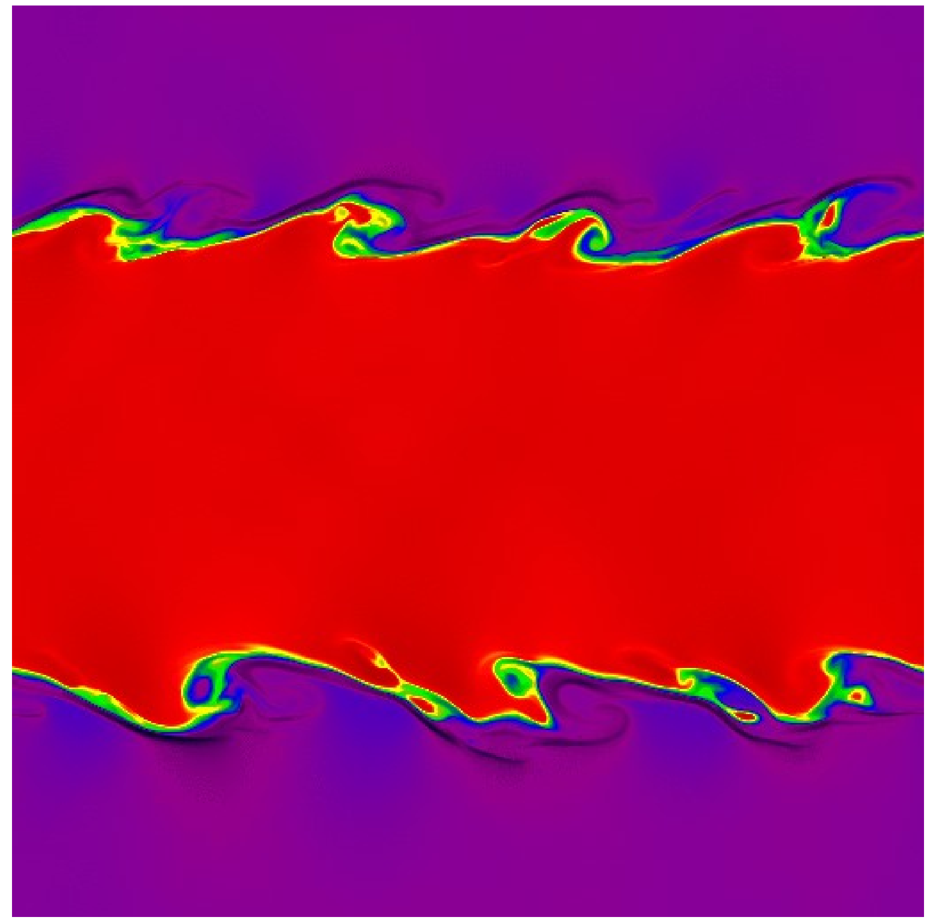
Instabilities in jet flows

Kelvin Helmholtz instability

-> HD simulations of shearing fluid layers

MHD simulation: aligned magnetic field stabilises KHI <---> tension balances centrifugal force



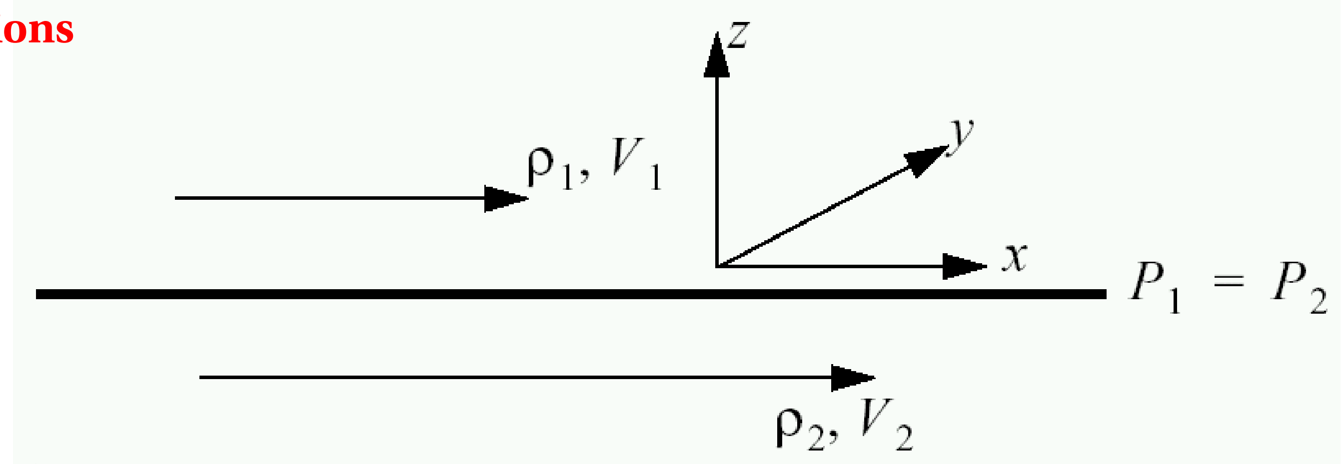


Time step 5.0; box of 512 x 512 cells; density 0.9 ...2.1 ; seed disturbance $\Delta v \sim 0.01$

[vx]_1 = -0.5 ; **[vx]_2** = 0.5 ; $\rho_1 = 1$; $\rho_2 = 2$, $P_1 = P_2$;

$M_1 = 0.377$, $M_2 = 0.267$, **B = Bx** = const = 0.5 $\mathrm{sqrt}(4\pi)$

Instabilities in jet flows



Kelvin Helmholtz instability

Derivations
(see lecture notes Bicknell)

-> mass & momentum conservation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho V_i) = 0 \qquad \rho\left[\frac{\partial V_i}{\partial t} + V_j \frac{\partial V_i}{\partial x_j}\right] + \frac{\partial P}{\partial x_i} = 0$$

-> disturbance:

$$\rho = \rho_0 + \rho' \qquad V_i = V_{0,i} + V_i'$$

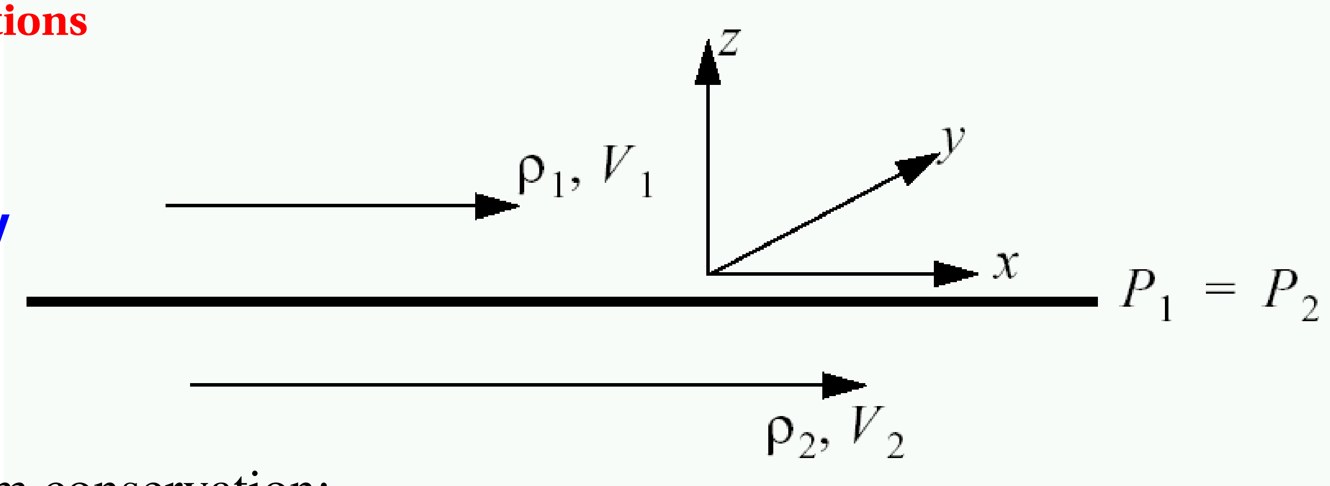
-> implying that:

$$\rho V_i = \rho_0 V_{0,i} + \rho_0 V_i' + \rho' V_{0,i}$$

$$\frac{\partial V_i}{\partial x_j} = (V_{0,j} + V_j')\frac{\partial}{\partial x_j} V_i' = V_0 \frac{\partial}{\partial x} V_i'$$

(used for perturbed mass & momentum conservation)

Instabilities in jet flows



Kelvin Helmholtz instability

derivations ...

-> perturbed mass & momentum conservation:

$$\frac{\partial \rho_1}{\partial t} + \rho_0 \frac{\partial}{\partial x_j} V_j' + V_{0,j} \frac{\partial}{\partial x_j} \rho' = 0$$

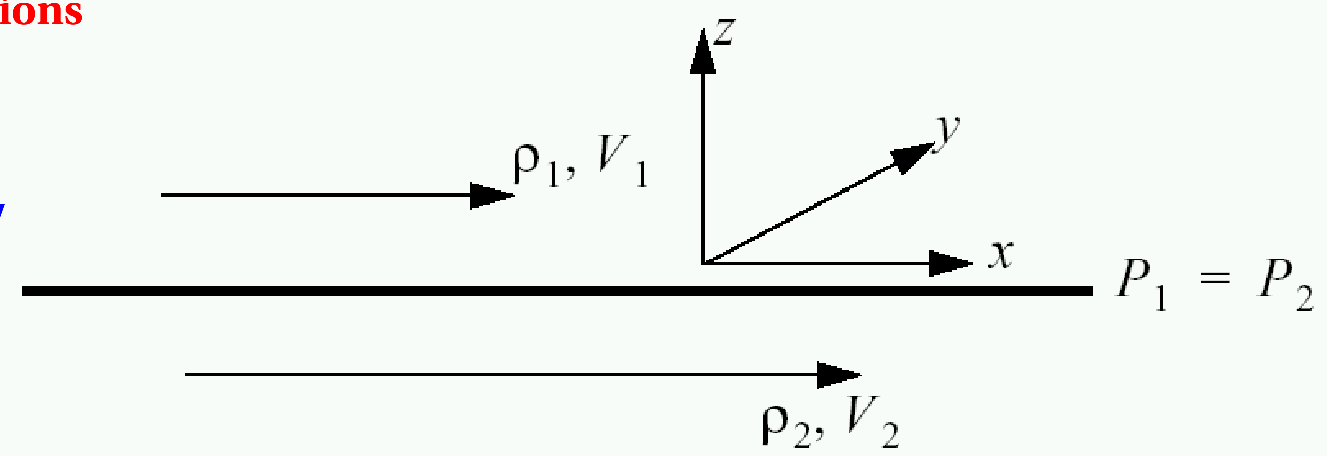
$$\rho_0 \left[\frac{\partial V_i}{\partial t} + V_0 \frac{\partial}{\partial x} V_i' \right] + \frac{\partial}{\partial x_i} P' = 0$$

-> substitute density by pressure using (note density might be discontinuous, pressure not)

$$\begin{Bmatrix} \dfrac{\partial}{\partial t} \\ \dfrac{\partial}{\partial x_i} \end{Bmatrix} \rho = \frac{1}{c_s^2} \begin{Bmatrix} \dfrac{\partial}{\partial t} \\ \dfrac{\partial}{\partial x_i} \end{Bmatrix} P$$

Instabilities in jet flows

Kelvin Helmholtz instability



derivations ....

-> summary of perturbed equations:

$$\left[\frac{\partial}{\partial t}P' + V_0\frac{\partial}{\partial x}P'\right] + \rho_0 c_0^2 \frac{\partial}{\partial x_j}V_j' = 0$$

$$\rho_0\left[\frac{\partial V_i}{\partial t}' + V_0\frac{\partial}{\partial x}V_i'\right] + \frac{\partial}{\partial x_i}P' = 0$$

-> apply wave ansatz for perturbed quatities:

$$P' = A \exp i[k_x x + k_y y + k_z z - \omega t]$$

$$V_i' = A_i \exp i[k_x x + k_y y + k_z z - \omega t]$$

-> with $\rho c_0^2 = \gamma P_0$ we have

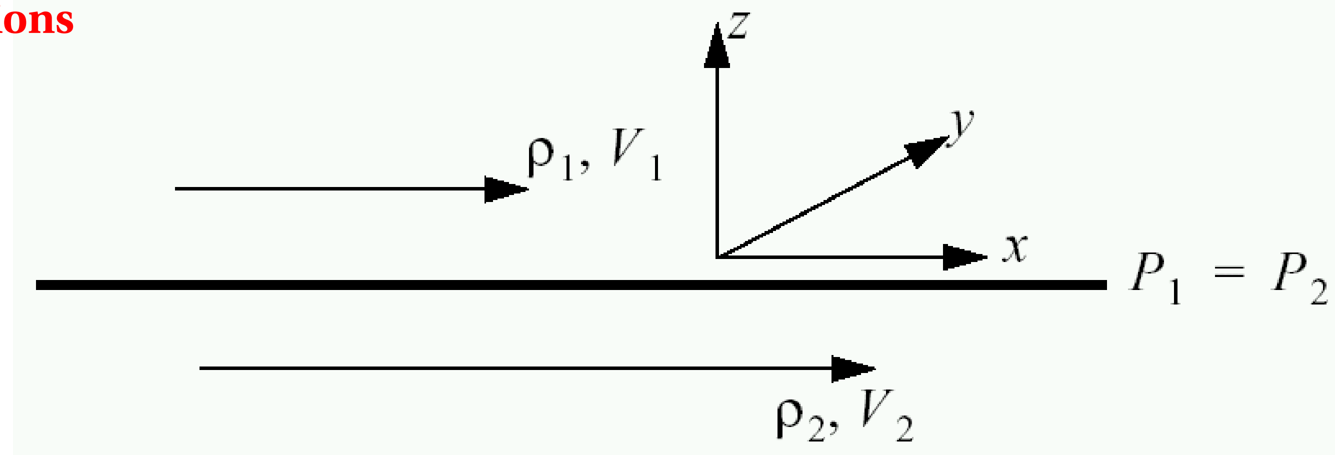
$$-i(\omega - k_x V_0)A + \gamma P_0(i k_j A_j) = 0$$

$$-i\rho_0(\omega - k_x V_0)A_i + i k_i A = 0$$

Instabilities in jet flows

Kelvin Helmholtz instability

derivations ...



-> rewrite wave vector, parallel component parallel to interface

$$\boldsymbol{k} = (k_x, k_y, k_z) = (\boldsymbol{k}_{\|}, k_z)$$

$$k_x = k_{\|}\cos\phi \qquad k_y = k_{\|}\sin\phi$$

$$k^2 = k_{\|}^2 + k_z^2 = k_i k_i$$

-> new perturbed equations (multiplied by k_||) -> **dispersion relation:**

$$(\omega - k_{\|} V_0 \cos\phi)^2 = \frac{\gamma P_0}{\rho_0} k^2 = c_0^2 k^2 = c_0^2 (k_{\|}^2 + k_z^2)$$

-> this is the dispersion relation of sound waves!

-> for the two sides of the interface:

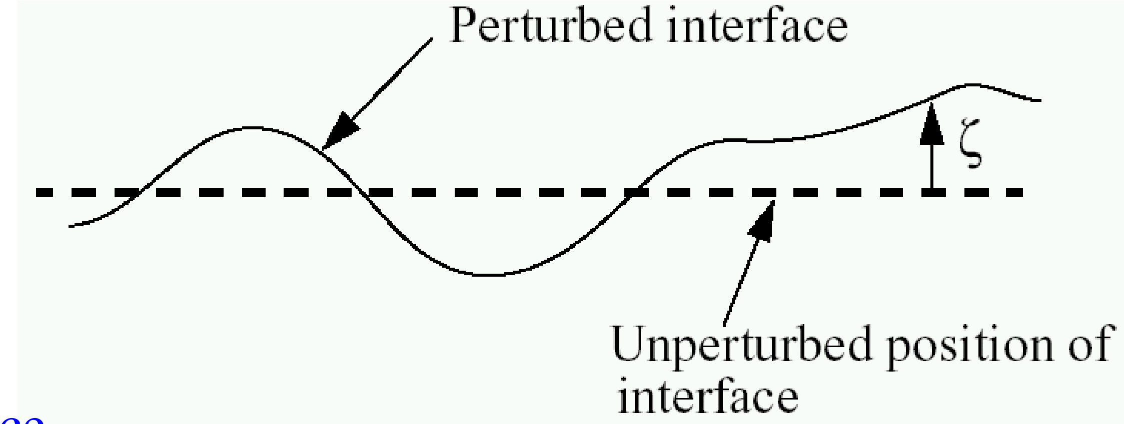
$$(\omega - k_{\|} V_1 \cos\phi)^2 = c_1^2 k^2$$

$$(\omega - k_{\|} V_2 \cos\phi)^2 = c_2^2 k^2$$

Instabilities in jet flows

Kelvin Helmholtz instability

derivations ...



-> now check for displacement of interface ....

$$\frac{\partial\zeta}{\partial t} + V_0\frac{\partial\zeta}{\partial x} = V_z' = A_z \exp i[k_x x + k_y y + k_z z - \omega t]$$

-> wave ansatz for z-displacement: $\zeta = B_z \exp i[k_x x + k_y y + k_z z - \omega t]$

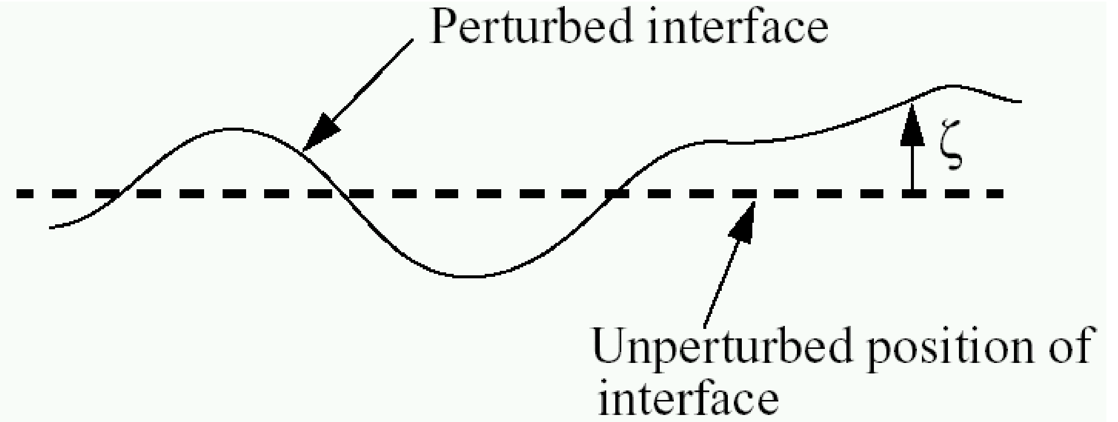
-> consider that 1) ***P***, ***ζ*** are continuous, 2) ***ρ*** is not, and 3) boundary conditions

-> equation for K-H instability:

$$\frac{\dfrac{V_{\rm ph}'^2}{c_1^2} - 1}{\dfrac{\gamma_1^2 V_{\rm ph}'^4}{c_1^4}} = \frac{\dfrac{(V_{\rm ph}' - \Delta V\cos\phi)^2}{c_2^2} - 1}{\dfrac{\gamma_2^2 (V_{\rm ph}' - \Delta V\cos\phi)^4}{c_2^4}}$$

with phase velocity $V_{\rm ph}' = \dfrac{\omega'}{k_{||}}$ and velocity difference $\Delta V = V_2 - V_1$

Instabilities in jet flows



Kelvin Helmholtz instability

derivations ...

-> define phase velocity of perturbation relative to sound speed in frame of lower stream and relative Mach number of two streams in direction of perturbation (-> ϕ):

$$x = \frac{V_{\mathrm{ph}}'}{c_1} \qquad m = \frac{\Delta V \cos\phi}{c_1}$$

-> basic dispersion relation for compressible KHI:

implicit 6th order polynomial equation: $$\frac{x^2-1}{x^4} = \frac{\gamma_1^2}{\gamma_2^2}\frac{c_2^2}{c_1^2}\left[\frac{(x-m)^2 - c_2^2/c_1^2}{(x-m)^4}\right]$$

-> example solution for instability for case $\gamma_1 = \gamma_2$

-> eq. (**) factorizes (quartic & quadratic part): roots of quadratic are stable solutions

-> roots of quartic correspond to instability if $m^2 < 8$

resp. correspond to stability $m = \frac{\Delta V \cos\phi}{c_1} > \sqrt{8}$

(critical angle for instability ...)

-> growth rate for magnetized KHI ~ Alfven crossing time

Instabilities in jet flows

Current-driven (CD) instabilities

-> poloidal electric current equivalent to toroidal magnetic field:

rot B ~ j integration -> **$R B_\phi = I$** (**“identity”**)

-> current carrying jets:

-> KH modes slightly stabilised compared to longitudinal field-only case (at same Mach number)

-> liable to additional pure MHD instabilities :

-> driven by electric current along the magnetic field (internal instability)

-> thermal pressure gradient in the jet (local instability -> turbulence)

-> CD instability growth on time scales < Alfven crossing time scale

-> depending on: ratio pitch length / jet radius ~ $r B_z / B_\phi / r_{jet}$

-> small pitch angle -> strongly unstable CD modes

-> sausage & kink modes: most dominant modes of CD instability

Instabilities in jet flows

Current-driven (CD) instabilities

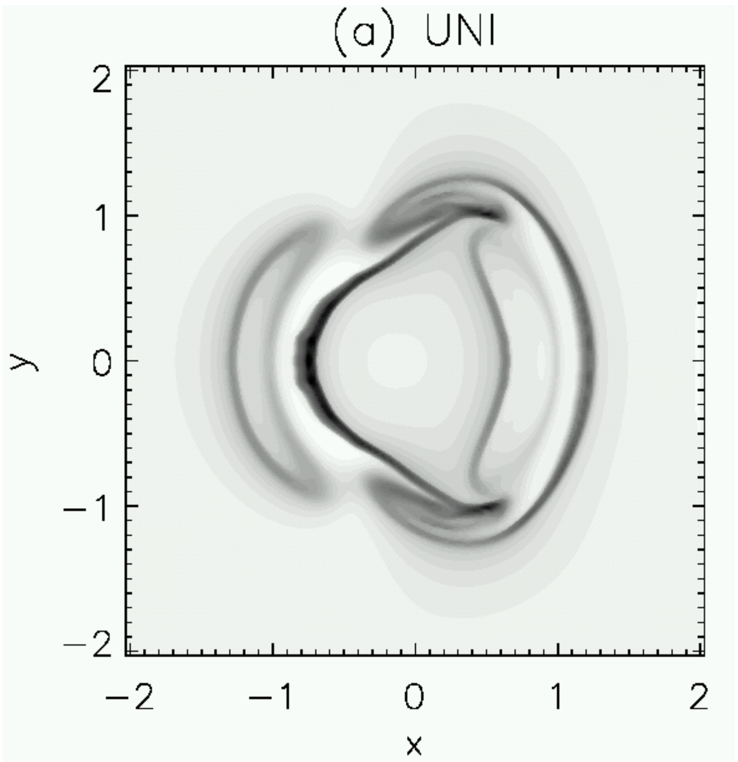
-> current carrying jets:

-> non-linear evolution of CDIs by MHD simulations (e.g. Baty & Keppens '02):

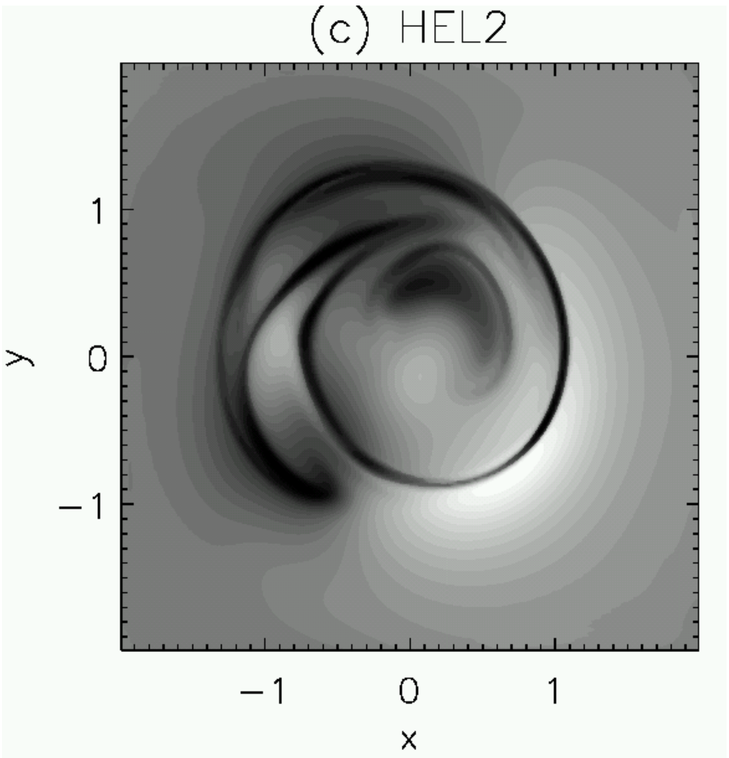
"UNI": $B_\phi = 0$, $B_z = 0.25$

"HEL1": $B_\phi < 0.4$, $B_z = 0.25$

Setup: 3D box: 200x200x100; $M=1.26$, $M_A=6.52$, $M_F= 1.24$



-> density distribution across the jet (linear scale 0.5 ...1.3)



-> mode coupling of CD with KH modes.

-> CD modes may saturate KH surface vortices, help to avoid jet disruption

Instabilities in jet flows

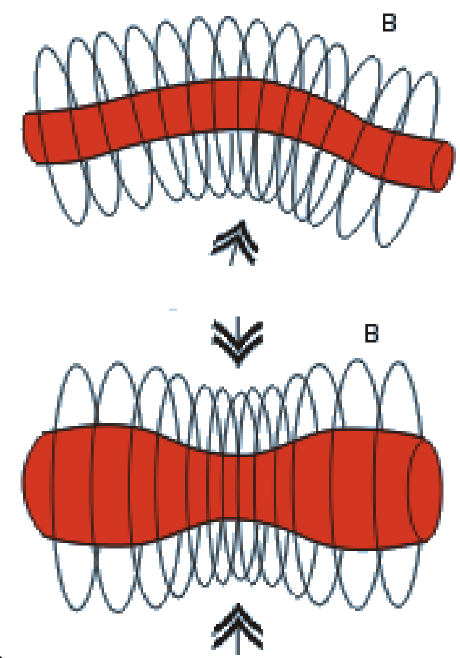
Remarks on mode classification:

-> wave ansatz for different coordinate directions,
e.g. cylindrical jet, cylindrical coordinate system:

$$f' = f'(r) \exp\left(i \left(kz + m\phi - \omega t \right) \right)$$

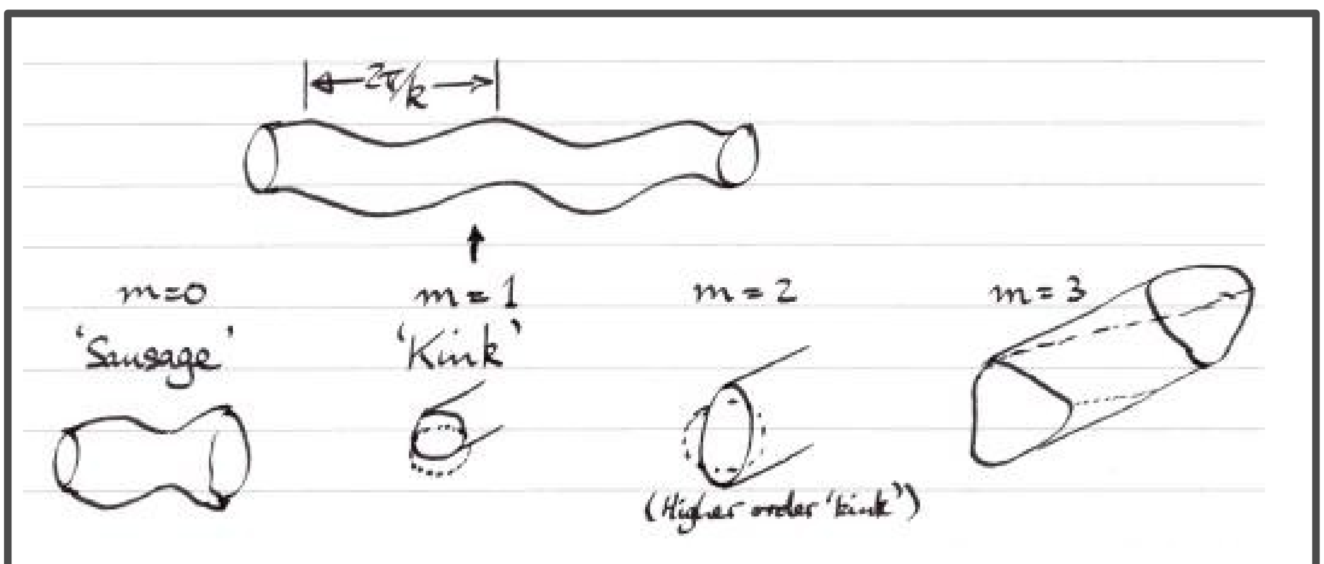
-> m=0 mode is sausage (pinch) mode; m= 1 is kink (helical) mode
m= 2 is higher order kink, m= 3 involves torsional kink

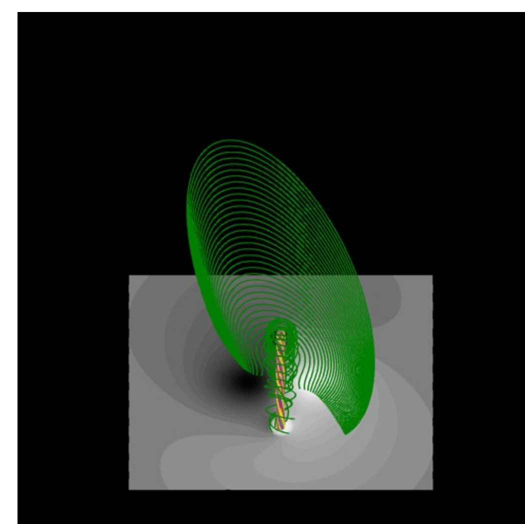
-> follows also from Fourier expansion of e.g. unstable flow



www. aldebaran. cz /astro fyzika/plazma/phenomena_en. html

from Hutchinson lecture





Solar flux tube, T

Shocks in jets and outflows

Basic principles:

-> compressible fluid: disturbance travels within surrounding medium: acoustic wave

-> infinitesimal disturbance: wave form is conserved, linear wave (linearized equations)

-> finite disturbance: non-linear equations, non-linearv acoustic wave

-> wave form steepens -> shock wave

-> steepening of non-linear waves: sinusoidal wavelet steepens into triangular shock wave:

high density part of wave has higher sound speed, travels faster than average

-> wave top catches up with bottom -> wave profile steepens

-> extreme example: compressible high speed fluid (jet) rams into low speed fluid (ISM)

-> shock wave traveling on front of jet

-> structure of thin shock layer defined by viscous processes

-> deceleration = momentum exchange, heating, compression defined by viscosity

-> shock thickness $\Delta x \sim L$ mean free path:

-> astrophysical plasmas thin -> mean free path long, **"collisionless"** shocks

-> momentum exchange by magnetic field compression

-> Draine (1980): J-shocks (strong, thin, viscous), C-shocks (weak, wide, magnetic)

Shocks in jets and outflows

Hydrodynamic (viscous) shocks (J-shocks):

-> consider hydrodynamic equations in one direction:

$$\frac{d}{dx}(\rho u)=0 \quad \frac{d}{dx}\left(\rho u^2+P-\frac{4}{3}\mu\frac{du}{dx}\right)=0 \quad \frac{d}{dx}\left[\rho\left(\frac{1}{2}u^2+\epsilon\right)u+\left(P-\frac{4}{3}\mu\frac{du}{dx}\right)u-\kappa\frac{dT}{dx}\right]=0$$

-> frictional momentum flux: $\pi_{xx}=\frac{4}{3}\mu\frac{du}{dx}$

-> integration -> conservation laws: $\rho u=const$

$$\rho u^2+P-\frac{4}{3}\mu\frac{du}{dx}=const. \qquad \rho u\left(\frac{1}{2}u^2+\epsilon+\frac{P}{\rho}\right)-\frac{4}{3}\mu u\frac{du}{dx}-\kappa\frac{dT}{dx}=const.$$

-> shock thickness:

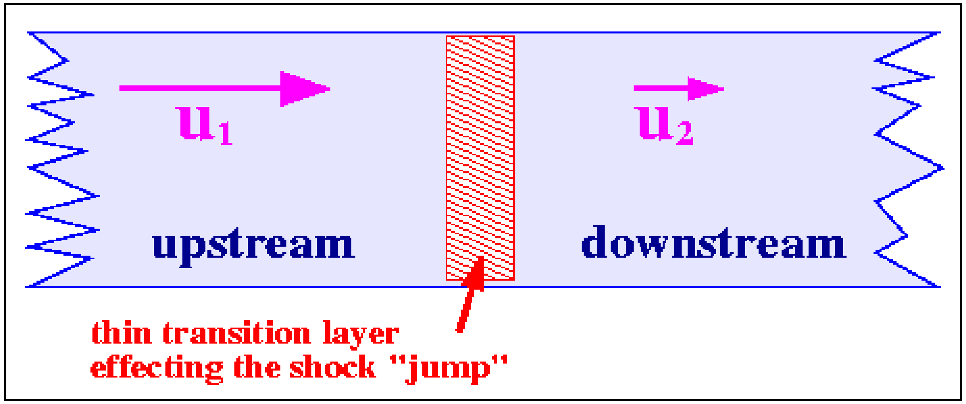
in shock transition layer: momentum flux of same order as other terms

$$-\frac{4}{3}\mu\frac{du}{dx}\simeq\rho\nu\frac{\Delta u}{\Delta x}\simeq\rho u^2 \quad \text{->} \quad \Delta x\simeq\nu\frac{\Delta x}{u^2}$$

for strong shocks: $\Delta u \sim u$ and $u \sim v\_T$ since u becomes subsonic

since for kinematic viscosity $\nu \sim L\, v\_T$ =>> $\Delta x \sim L$

Shocks in jets and outflows



Rankine-Hugoniot jump conditions:

-> conservation laws upstream and downstream of shock layer (derivatives neglected):

--> Rankine-Hugeniot jump conditions

$$\rho_1 u_1 = \rho_2 u_2 \qquad \rho_1 u_1^2 + P_1 = \rho_2 u_2^2 + P_2 \qquad u_1\left(\frac{1}{2}\rho_1 u^2 + \rho_1 \epsilon + P_1\right) = u_2\left(\frac{1}{2}\rho_2 u_2^2 + \rho_2 \epsilon + P_2\right)$$

-> solutions for R-H conditions: apply polytropic gas law $P \sim \rho^{\gamma}$, define upstream Mach number $M_1 \equiv u_1 / c_s$ with sound speed $c_s \equiv \gamma P/\rho$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1) M_1^2}{(\gamma+1)+(\gamma-1)(M_1^2-1)} = \frac{u_1}{u_2} \qquad \frac{P_2}{P_1} = \frac{(\gamma+1)+2\gamma(M_1^2-1)}{\gamma+1}$$

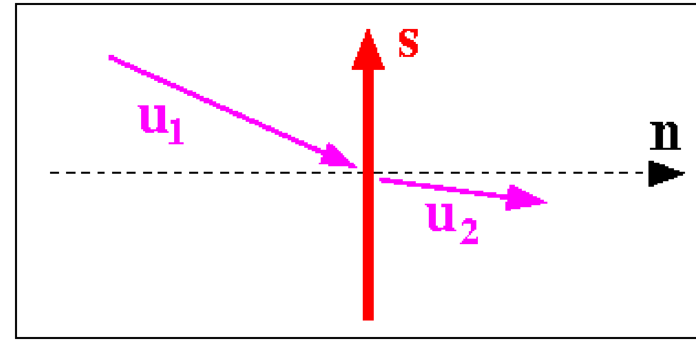
$$\frac{T_2}{T_1} = \frac{\left[(\gamma+1)+2\gamma(M_1^2-1)\right]\left[(\gamma+1)+(\gamma-1)(M_1^2-1)\right]}{(\gamma+1)^2 M_1^2}$$

Note that: $P_2 \geq P_1; \quad \rho_2 \geq \rho_1; \quad u_2 \leq u_1; \quad T_2 \geq T_1; \quad for\ M_1 \geq 1, \quad equality\ for\ M_1 = 1$

$$for\ M_1 \rightarrow \infty: \quad \frac{\rho_2}{\rho_1} = \frac{\gamma+1}{\gamma-1} = 4 \quad for\ \gamma = 5/3; \quad but\ \frac{P_2}{P_1}\ is\ unlimited$$

$$for\ M_1 > 1 \rightarrow M_2 < 1 \qquad [compressive\ shocks]$$

Shocks in jets and outflows



Hydromagnetic shocks:

-> plane for local dynamics defined by inflow velocity ***u*** and magnetic field ***B*** (in shock frame)

--> decomposition of vectors: ***s***-coordinate || to shock , ***n*** -coordinate _|_ to shock

-> Note: in addition to viscous stress tensor, now Maxwell stresses in order to exchange momentum, pressure etc

-> project MHD conservation laws || and _|_ to shock

- mass conservation: $\frac{\delta \rho}{\delta T}+\frac{\delta}{\delta x_k}(\rho u_k)=0$ -> $\frac{\delta}{\delta n}(\rho u_n)=\ldots$

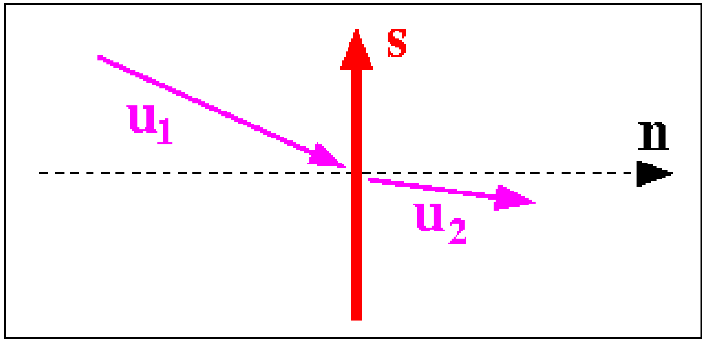
- momentum conservation $\frac{\delta}{\delta t}(\rho u_i)+\frac{\delta}{\delta x_k}(\rho u_i U_k+P\delta_{ik}-T_{ik})=-\rho\frac{\delta \Phi}{\delta x_i}=0$

-> $\frac{\delta}{\delta n}\left[\rho u_n u_n+P-\frac{1}{8\pi}(B_n^2-B_s^2)\right]=\ldots$ $\frac{\delta}{\delta n}\left[\rho u_s u_n-\frac{1}{4\pi}B_s B_n\right]=\ldots$

- induction equation $\frac{\delta \vec{B}}{\delta t}+\vec{\nabla}\times(\vec{B}\times\vec{u})=0$ -> $\frac{\delta}{\delta n}(B_n u_s-B_s u_n)=\ldots$

- no monopoles: $\vec{\nabla}\cdot\vec{B}=0$ -> $\frac{\delta B_n}{\delta n}=\ldots$

Shocks in jets and outflows



Hydromagnetic shocks – jump conditions

jump conditions from intergration of conservation laws:

$$[\rho u_n]_2 = [\rho u_n]_1$$

$$[B_n u_s - B_s u_n]_2 = [B_n u_s - B_s u_n]_1 \qquad [B_n]_2 = [B_n]_1$$

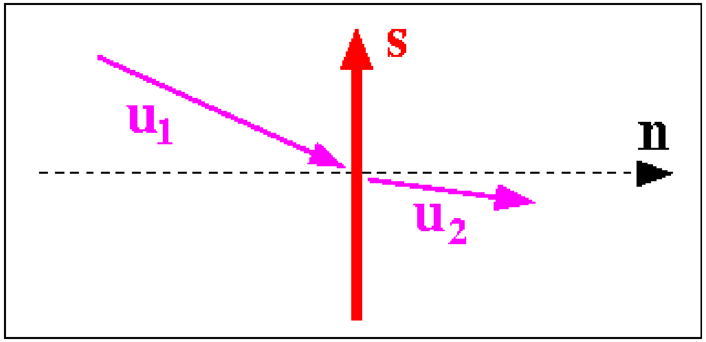
$$\left[\rho u_n u_s + \frac{B_s B_n}{4\pi}\right]_2 = \left[\rho u_n u_s + \frac{B_s B_n}{4\pi}\right]_1$$

$$\left[\rho u_n^2 + P + \frac{B_s^2}{8\pi}\right]_2 = \left[\rho u_n^2 + P + \frac{B_s^2}{8\pi}\right]_1$$

$$\left[\rho u_n \left(\frac{\gamma}{\gamma-1}\frac{P}{\rho} + \frac{1}{2}u^2\right) - \frac{1}{4\pi}(B_n u_s - B_s u_n) B_s\right]_2 =$$

$$\left[\rho u_n \left(\frac{\gamma}{\gamma-1}\frac{P}{\rho} + \frac{1}{2}u^2\right) - \frac{1}{4\pi}(B_n u_s - B_s u_n) B_s\right]_1$$

Shocks in jets and outflows



Hydromagnetic shocks – jump conditions

jump conditions -> behaviour of variables:

-> (ρ u_n) and B_n conserved across the shock (mass flux, magnetic flux conservation)

-> for parallel velocity $u_{s,2}$:

$$[u_s]_2 - [u_s]_1 = \frac{B_n}{4\pi \rho u_n} \left([B_s]_2 - [B_s]_1 \right)$$

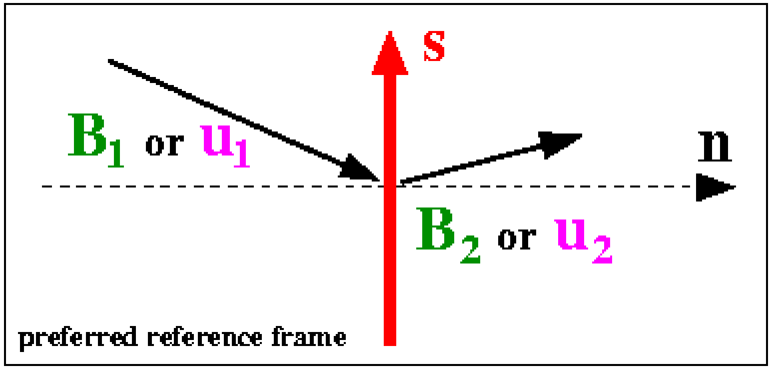
-> distinguishing features of MHD shocks:

- -> u_s is discontinous unlike in the non-magnetic case
- -> sudden deflections of tangential velocity possible

-> current sheet along shock:

$$j_s = \frac{c}{4\pi} \left([B_s]_2 - [B_s]_1 \right)$$

Shocks in jets and outflows



Hydromagnetic shocks – jump conditions

jump conditions --> shock classification:

-> for perpendicular velocity -> quartic relation to solve for $u_{n,2}$ (requires some math ...)

-> solutions if $u_{n,1}$ > MHD wave speeds

(transform (slide tangentially) in reference frame where u || B upstream & downstream)

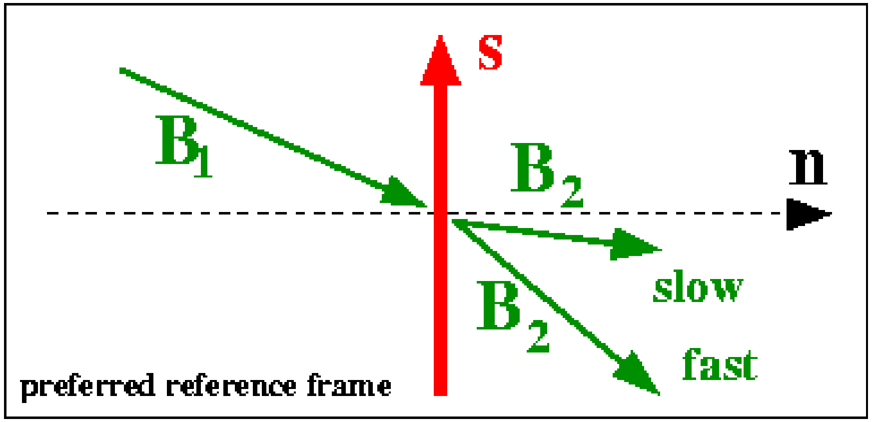
-> fast / slow shock : tangential magnetic field increases / decreases across the shock

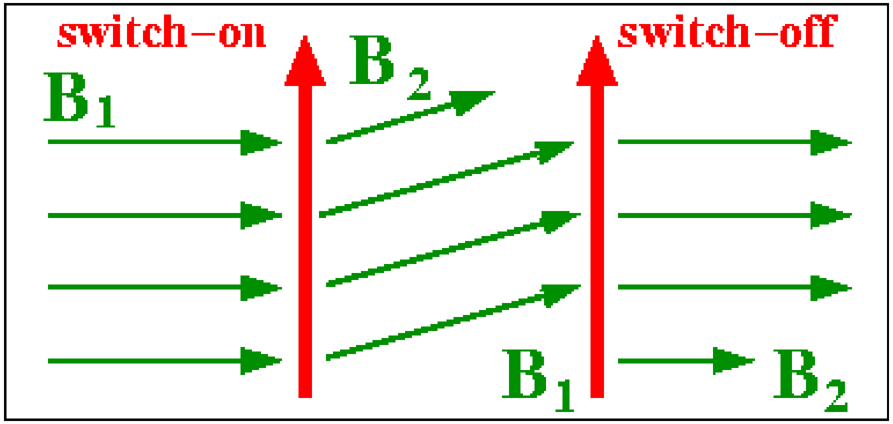
(in reference frame where u || B upstream & downstream)

-> switch off / on shock: $B_s = 0$ behind / ahead of slow shock

-> contact discontinuity: $u_s = 0$, $B_n > 0$ (between jet & bow shock, shocked ambient gas)

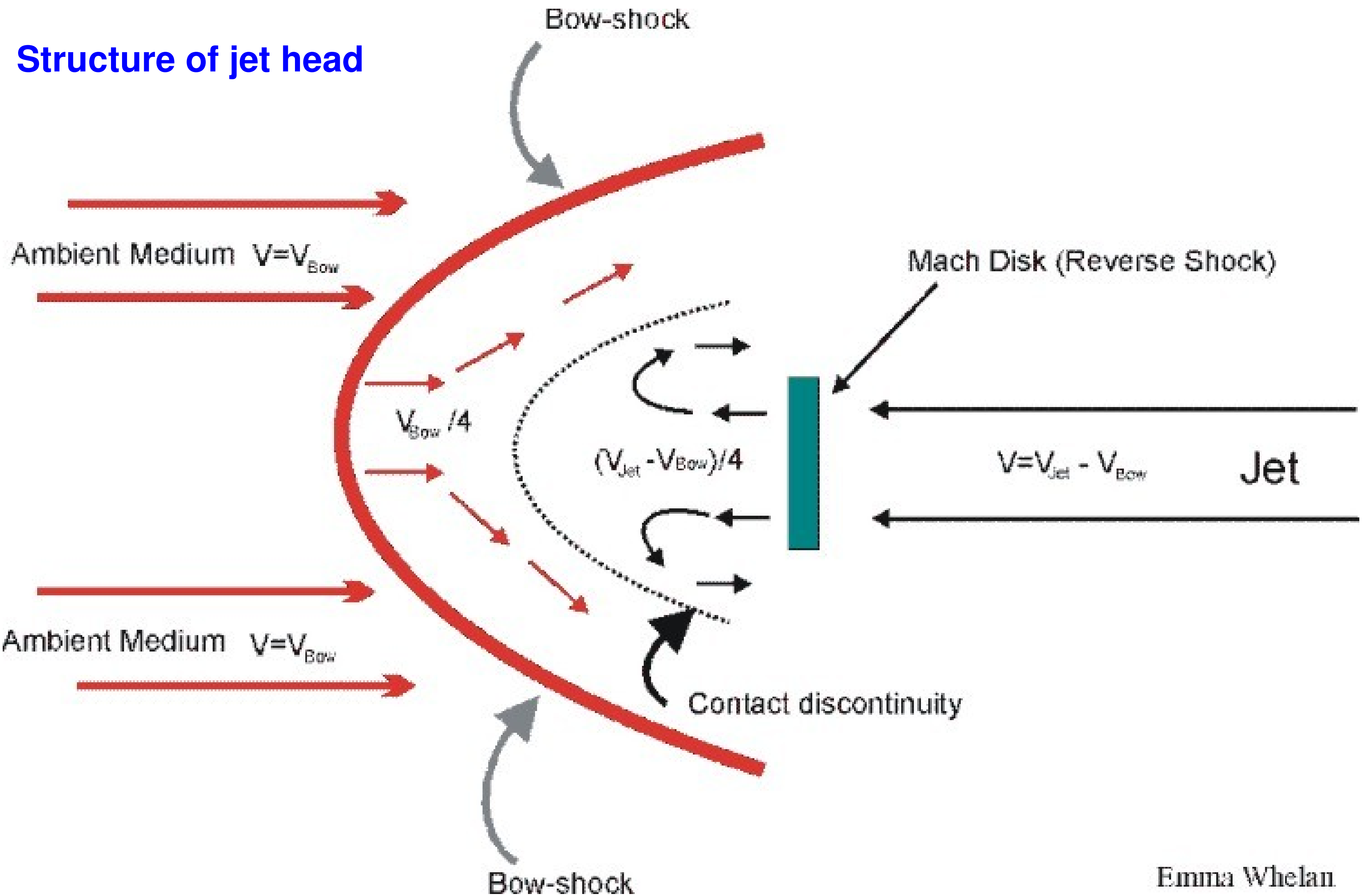
tangential discontinuity: $u_s = 0$, $B_n = 0$





Shocks in jets and outflows

Structure of jet head



Shocks in jets and outflows

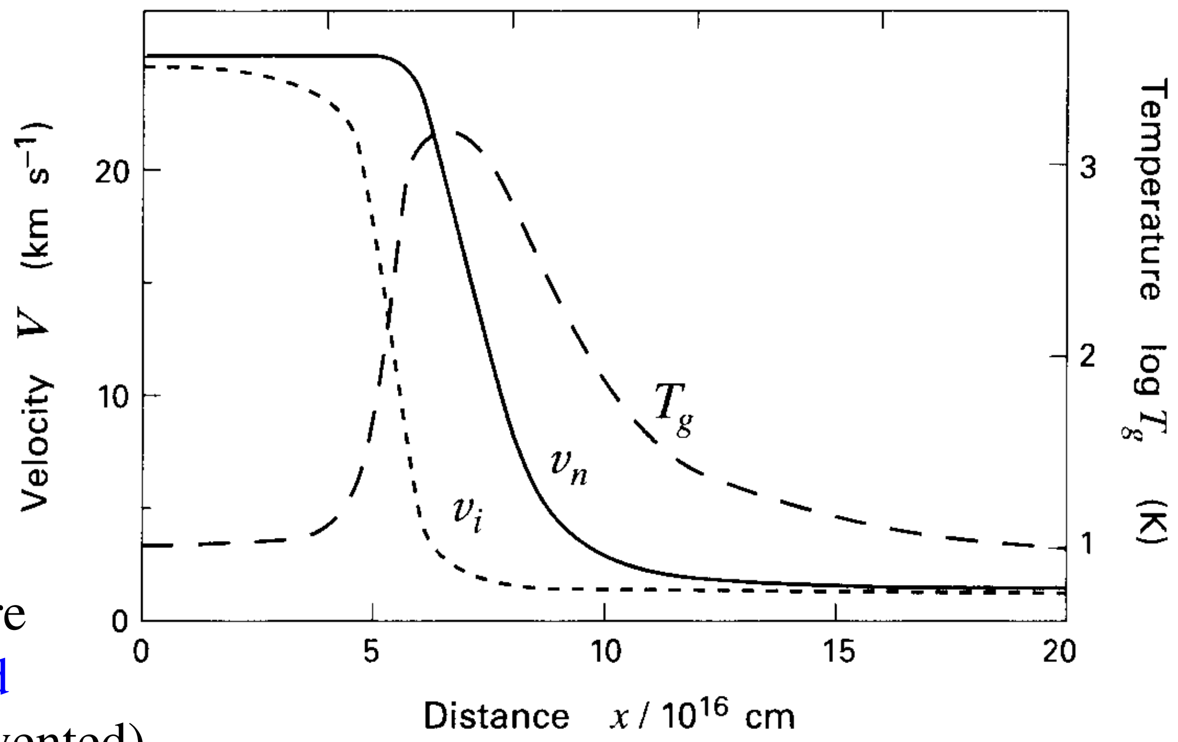
MHD shocks – C-shocks

-> magnetic shocks:
compress both field & gas

-> field compression absorbes momentum

-> upstream gas pressure / temperature lower than for un-magnetised fluid (e.g. molecular dissociation is prevented)

-> partially ionised gases:
neutral and charged particles may have different speed (e.g. ions braked by magnetic field, later brake neutrals by collisions / friction / viscosity)

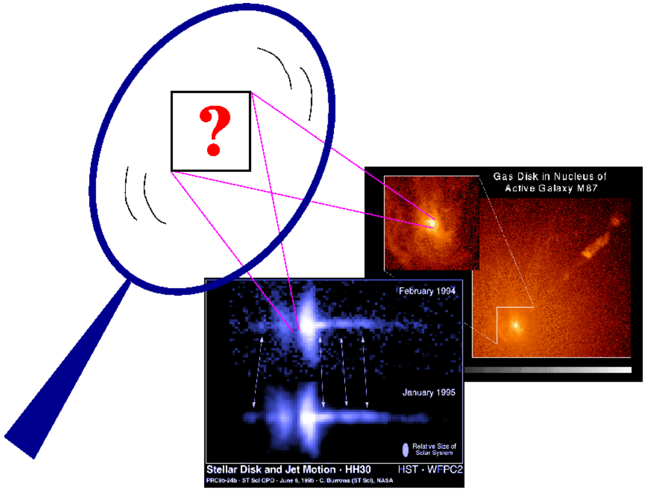


C-shock in molecular cloud, numerical results for pre-shock B = 100 µG. Ions decelerate prior to neutrals
Un-magnetic case would result in post-shock T = 34.000 K.

-> weak field: neutral matter undergoes J-shock to subsonic velocity
-> magnetic precursor: increasing field strength, deceleration of ionised gas
-> ion-neutral collisions increase precursor temperature/sound speed -> J-shock weakens

-> strong field: strong precursor, no viscous shock at all, as fluid density & temperature increase smoothly , velocity may remain supersonic

Outflows & Jets: Theory & Observations



10.10 Introduction & Overview ("H.B." & C.F.)
17.10 Definitions, parameters, basic observations (H.B.)
24.10 Basic theoretical concepts & models I (C.F.): Astrophysical models, MHD
31.10 Basic theoretical concepts & models II (C.F.) : MHD, derivations, applications
07.11 Observational properties of accretion disks (H.B.)
14.11 Accretion, accretion disk theory and jet launching (C.F.)
21.11 Outflow-disk connection, outflow entrainment (H.B.)
28.11 Outflow-ISM interaction, outflow chemistry (H.B.)
05.12 Theory of outflow interactions; Instabilities (C.F.)
12.12 Outflows from massive star-forming regions (H.B.)
19.12 Radiation processes - 1 (C.F.)
26.12 and 02.01 Christmas and New Year's break
09.01 Radiation processes - 2 (H.B.)
16.01 Observations of AGN jets (C.F.)
23.01 Some aspects of AGN jet theory (C.F.)
30.01 Summary, Outlook, Questions (H.B. & C.F.)