Lecture

Pre-main sequence evolution

Jets and outflows

Pre-main sequence evolution

Luminosity provided by quasistatic contraction of star; stage of hydrogen burning not yet reached, but protostellar accretion phase completed

Important consideration

Comparison of timescales

$t_{HK} = \frac{G M_*^2 / R_*}{L_*}$ Helmholtz-Kelvin timescale of quasistatic contraction

$t_{acc} < t_{HK}$ Protostars gains mass without changing structure dramatically

$t_{acc} > t_{HK}$ Arrival on ZAMS during accretion phase; object is still embedded

$t_{acc} \approx t_{HK}$ occurs at $8-10\ M_\odot$

$\Rightarrow$ There are no optically visible PMS stars for $M_* > 8\ M_\odot$

Indeed: Intermediate-mass PMS - Herbig Ae/Be-stars have masses up to $8\ M_\odot$

Evolutionary Tracks in HRD

Henyey Track (Henyey et al. 1955)

Nearly horizontal track in HRD with star in radiative equilibrium

$$L_{rad} \sim \left(\frac{M_*}{M_\odot}\right)^{11/2} \left(\frac{R_*}{R_\odot}\right)^{-1/2} \cdot L_\odot$$

Hayashi Track (Hayashi et al. 1962)

Vertical track in HRD; Star of given M_* and R_* has minimum temperature (completely convective)

Stars below 0.4 Msun reach the ~~star~~ ZAMS still fully convective

Remember: Birthline concept
Structure of protostars (and $\dot{M}$) sets initial $R_* = R_*(M_*)$; is several $R_\odot$ for $1 M_\odot$ star

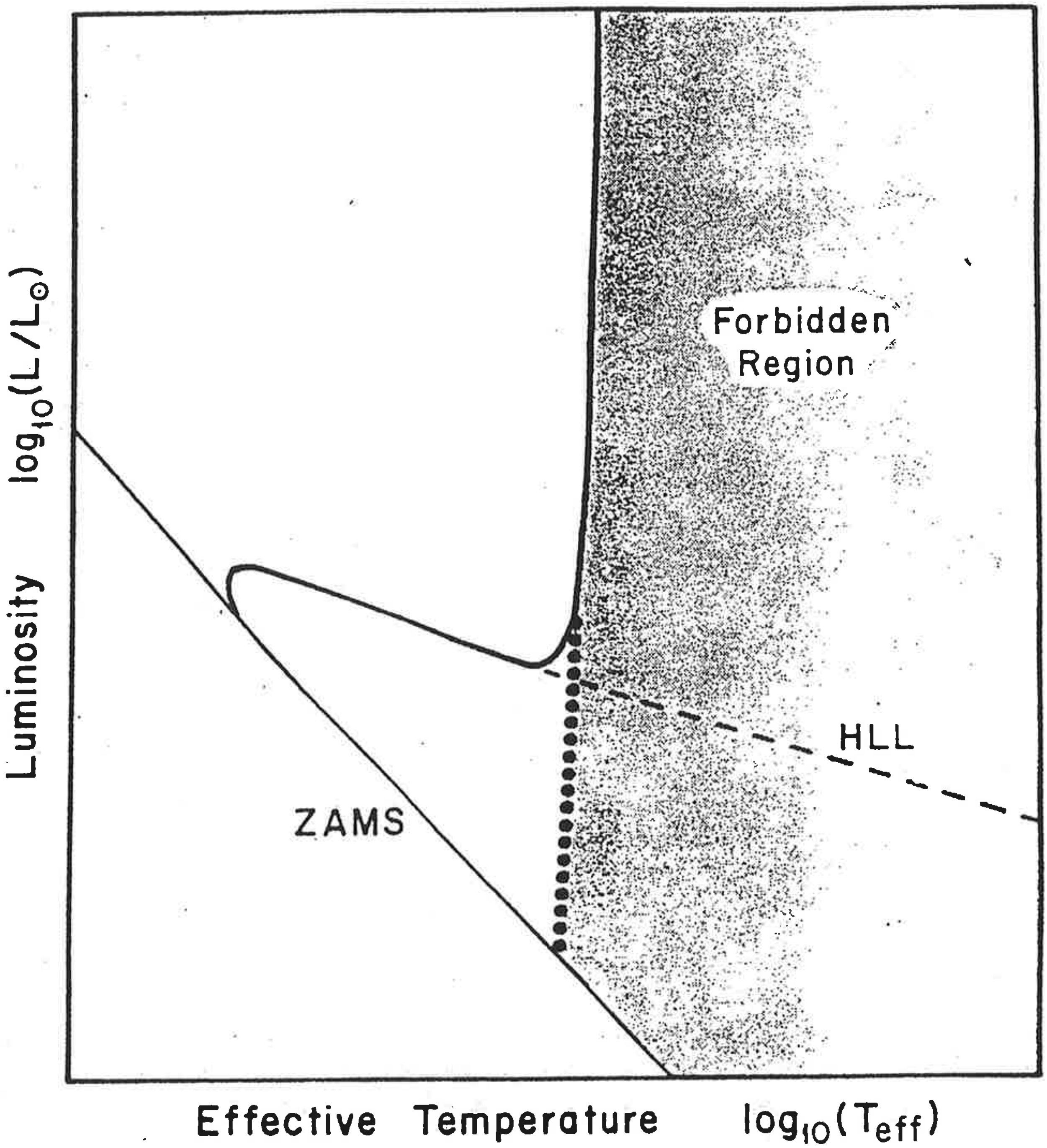


FIG. 1–Theoretical pre-main-sequence evolutionary tracks (schematic). A star of a given mass is first convective and descends a nearly vertical path, eventually turning onto the more horizontal radiative track discovered by HLL. The vertical path and its downward extension (dotted line) form the border of Hayashi's forbidden region (shaded) for stars of that mass.

Different Evolution for low-mass and intermediate-mass PMS stars.

<u>Low-mass stars (T Tauri stars) (up to 2 $M_\odot$)</u>

Shrinking releases grav. energy while surface temperature remains nearly constant. (Hayashi track). At some point $L < L_{crit}$ for radiation → Radiative core forms with shrinking outer convective layer; reaches radiative track (T, L raises) until hydrogen burning starts (ZAMS)

<u>Intermediate-mass stars (Herbig Ae/Be stars) (2-8 $M_\odot$)</u>

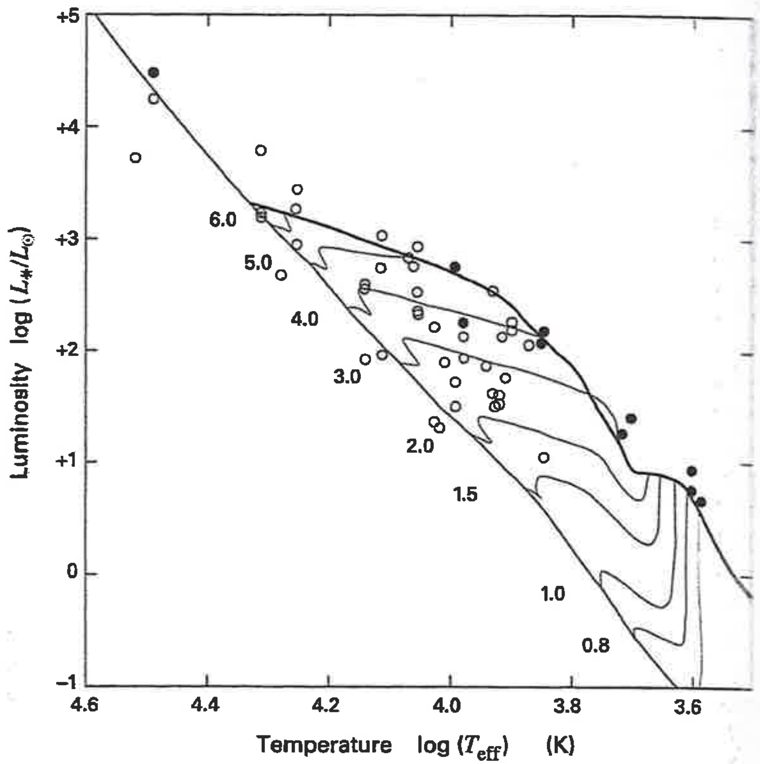
More massive objects are no longer convective in the protostellar phase, they reach the PMS evolution on radiative tracks; they do not have a phase of shrinking L although they also shrink; They always gain L and T via gravitational energy

Observational birthline

Stahler (1983):
In HRD of Taurus-Auriga, Orion, Ophiuchus and other SF regions → "Birthline" in HRD at which optically visible PMS objects exist

Explanation for solar-type stars:
Accretion comes to an end and $R_c = f(M_c)$ is provided by protostellar evolution and deuterium thermostat;
The birthline is then simply the position in the HRD of PMS stars with protostellar radii
(Remember: Protostellar radii are greater than MS values, but never by more than a factor of 10; L of PMS stars cannot exceed those along the ZAMS by more than 2 orders of magnitude)

Palla & Stahler : The Formation of Stars.
p. 580



Observational Sequence

- Class 0 objects $M_{env} \gg M_*$
  Not visible until MIR wavelengths
  Driving molecular outflows (shell. activity)

- Class I objects $M_{env} > M_*$
  Infrared to submm sources
  In general warmer than class ϕ

- Class II objects
  Optically visible PMS stars with disks
  (classical T Tauri stars)

- Class III objects
  Optically visible PMS stars without disks
  (weak-line T Tauri stars)

Jets and Outflows

Examples for optical jets and molecular outflows

Jets: $H\alpha$, [OI] 630.0 nm & 636.3 nm,
[SII] 671.7 & 673.1 nm, H_2, radio

Molecular Outflows: CO, SiO

General outflow properties

- Jet velocities 100 - 500 km/s, molecular outflow velocities 10-50 km/s (ambient molecular gas swept up by the higher velocity winds and jets)
- Estimated dynamical age 10^3 to 10^5 yrs
- Size between 0.1 and 1pc

Thermally driven winds (coronal stellar winds)?

Such winds not important when $c_s < v_{esc}$

Temperature in T Tauri winds $\leq 10^4$ K =>

$c_s \lesssim 10$ km/s $< v_{esc} = 100$ km/s

Winds driven by radiation force?

Momentum fluxes of molecular outflows much larger than photon momentum flux L_* / c

Importance

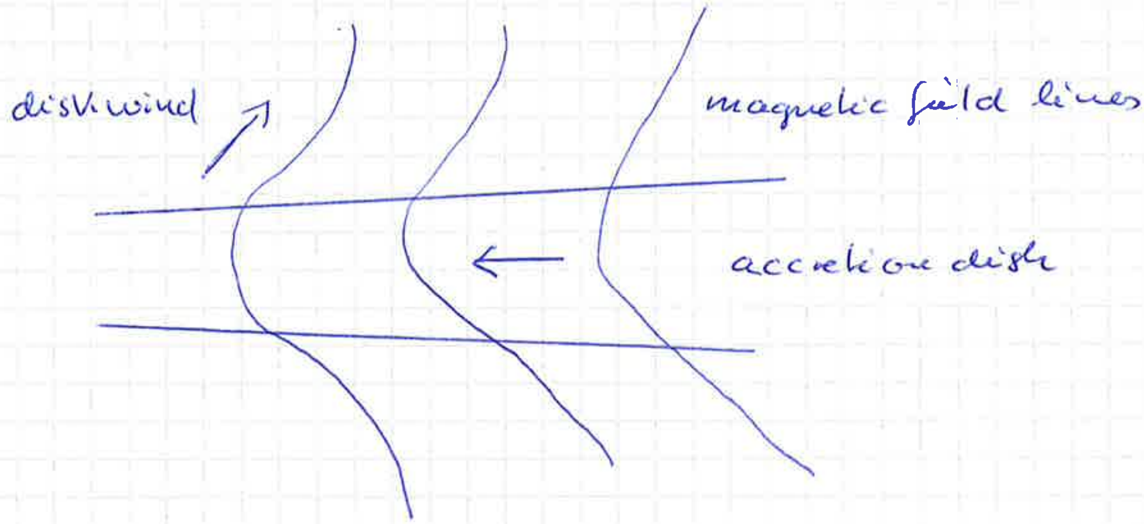
a) Entrain large amounts of cloud mass with high energies

b) Can disrupt cores to stop accretion

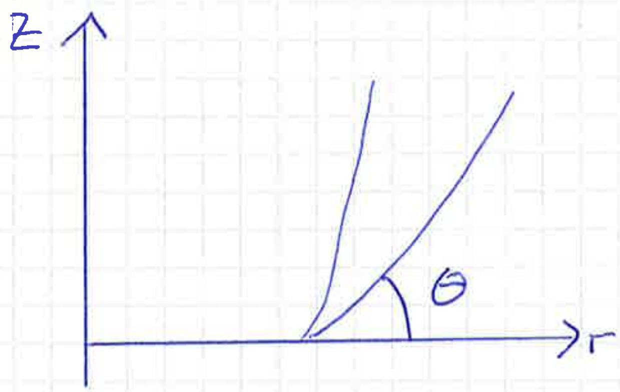
c) may trigger collapse in nearby cores

d) Heat cloud via shocks & alter chemistry

Favored mechanism for launching outflows
-> magnetocentrifugal acceleration from the circumstellar disk



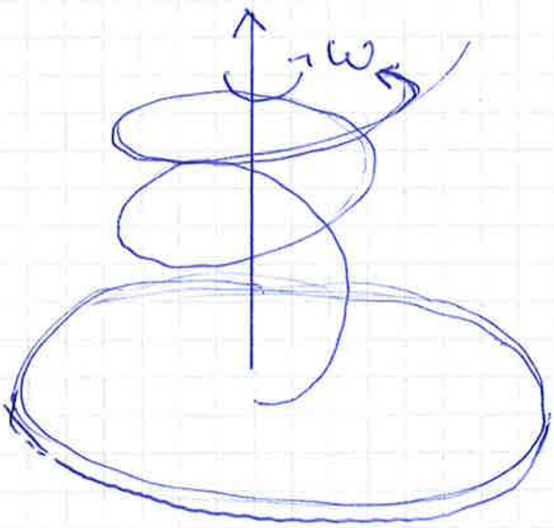
For a particle in a rotating disk (wire) one can show that the particle is accelerated when (angle between rotation axis and magnetic field direction) is larger than 30°, ~~for Θ > 60°~~



Θ < 60°
particle is accelerated

(Blandford & Payne 1982)

Magnetic field lines also collimate outflows along the rotation axis; Collimation comes from toroidal field which is build up in the rotating flow ($B_\phi / B_p > 1$; collimation via Lorentz force)

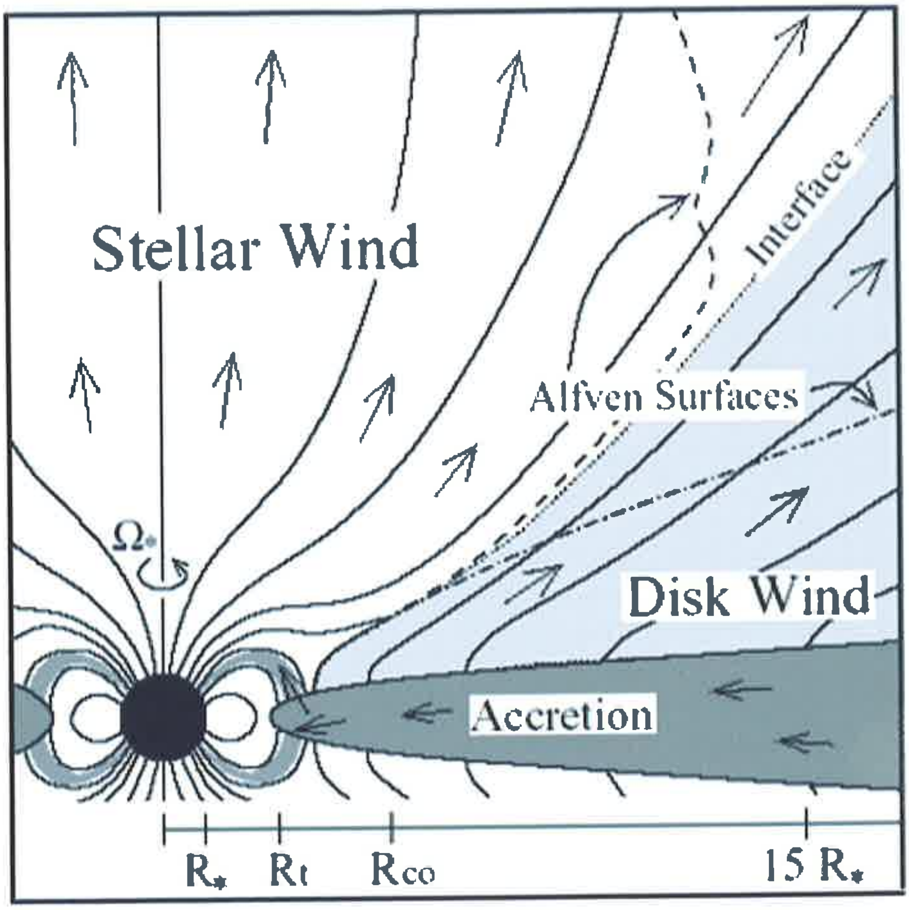


Two types of wind launching

a) X-wind (Shu et al. 1994)
Launching from a small area just at co-rotation (~ 0.03 AU)

b) Magnetocentrifugal disk winds (Pudritz & Norman 1983)
Launching over larger disk area

Winds can transport considerable amount of disk angular momentum



Stellar Wind
Interface
Alfven Surfaces
Disk Wind
Accretion
Ω*
R*
Rt
Rco
15 R*

Matt (2005)

Molecular Outflows

- Molecular outflow masses much larger than stellar masses → swept-up entrained gas
- Momentum in outflow larger than L_*/c → driven by underlying jets

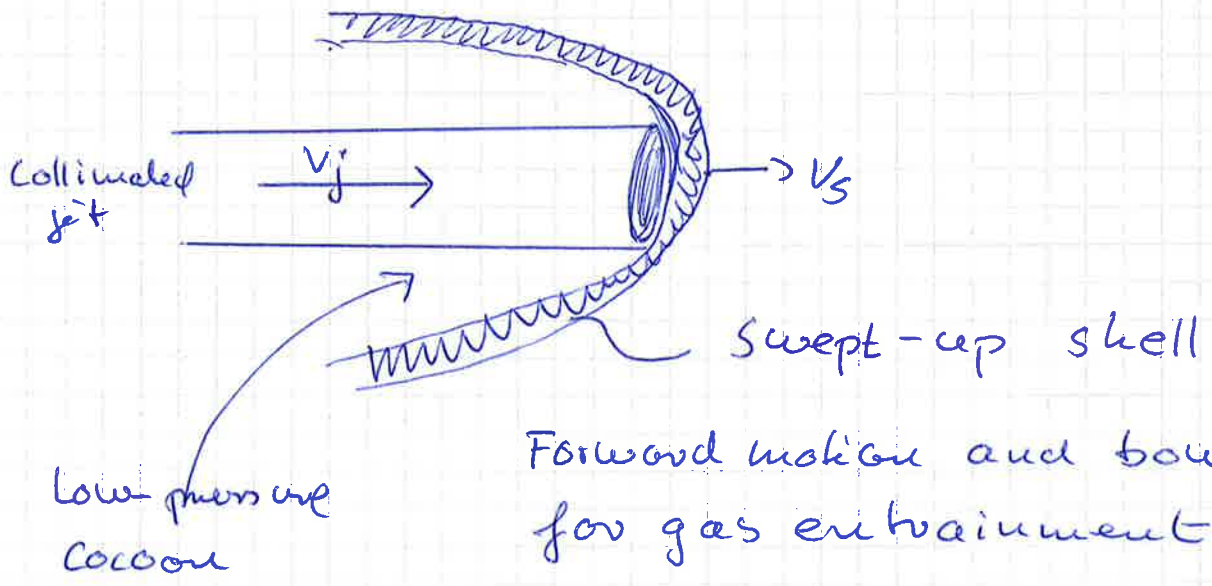
Energy-driven outflows

Jet-energy conserved in a pressurized bubble (adiabatic shock) → large transverse velocities as the bubble expands (not observed!)

Momentum-driven outflows

Momentum is conserved in interaction (radiative shock) → only dense plug at front

Intermediate solution with highly dissipative shock required → forward motion and bow shock



Forward motion and bow-shock for gas entrainment

A large variety of entrainment models have been discussed:

<u>Important model</u>

Jet-bow shock model

-> bow shocks are formed at head of jet

- High pressure gas is ejected sideways
- broader bow shock entraining ambient gas
- Episodic ejection produces chains of knots and shocks

It reproduces many of the observations, especially the "Hubble law" (linear increase of velocity with distance)