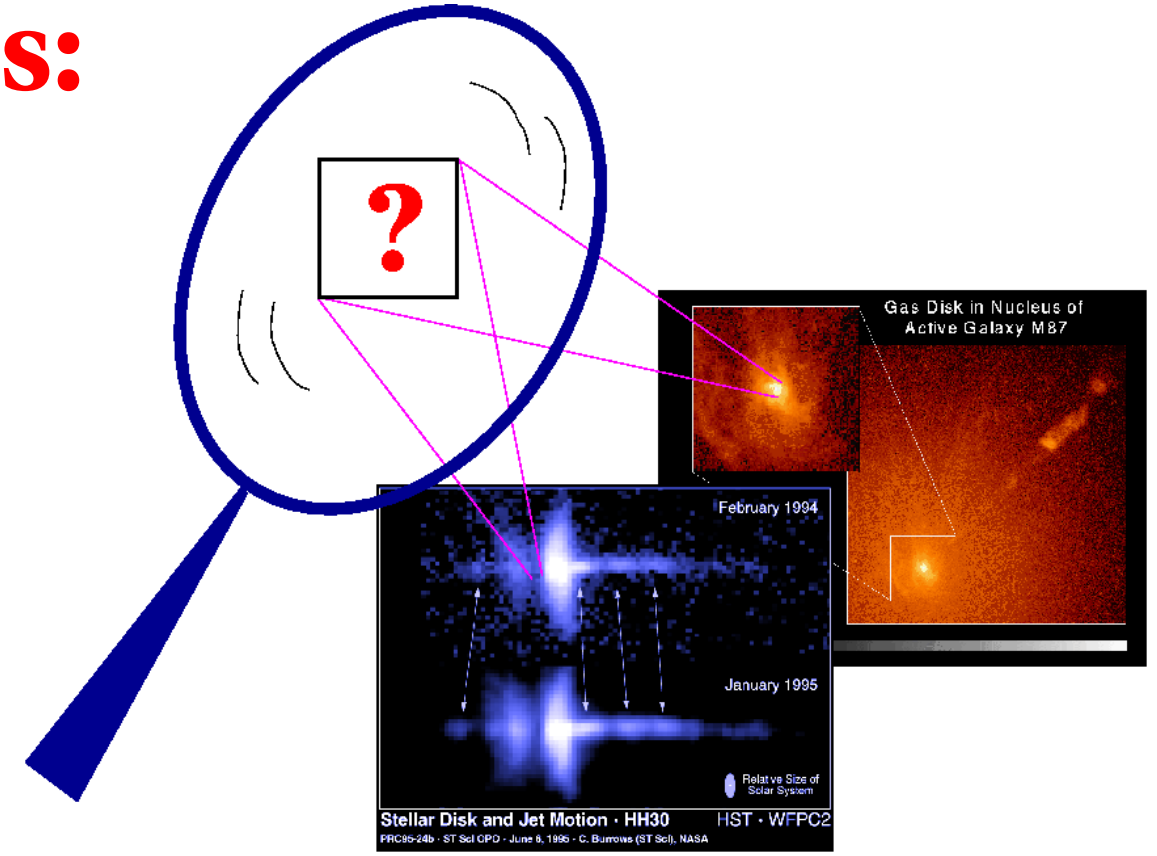
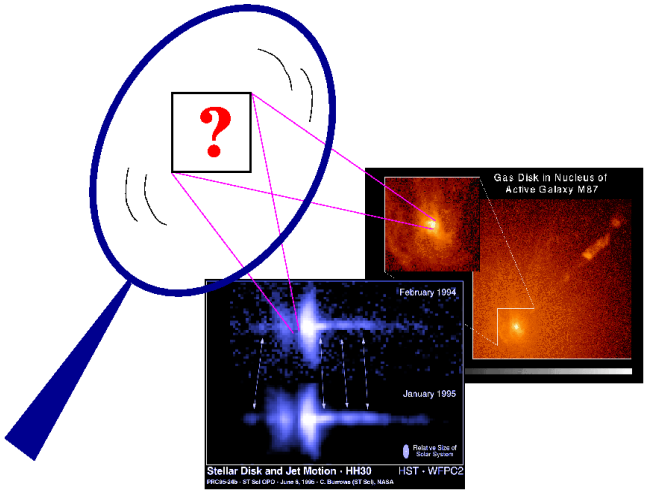
Outflows & Jets: Theory & Observations



Lecture winter term 2008/2009

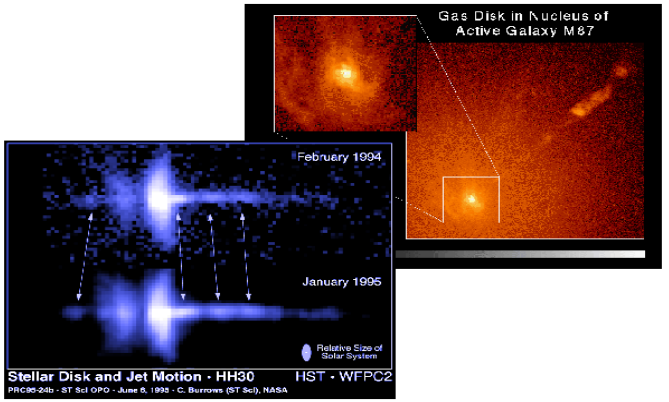
Henrik Beuther & Christian Fendt

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: forbidden emission lines (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.)

Summary of lecture – theory part



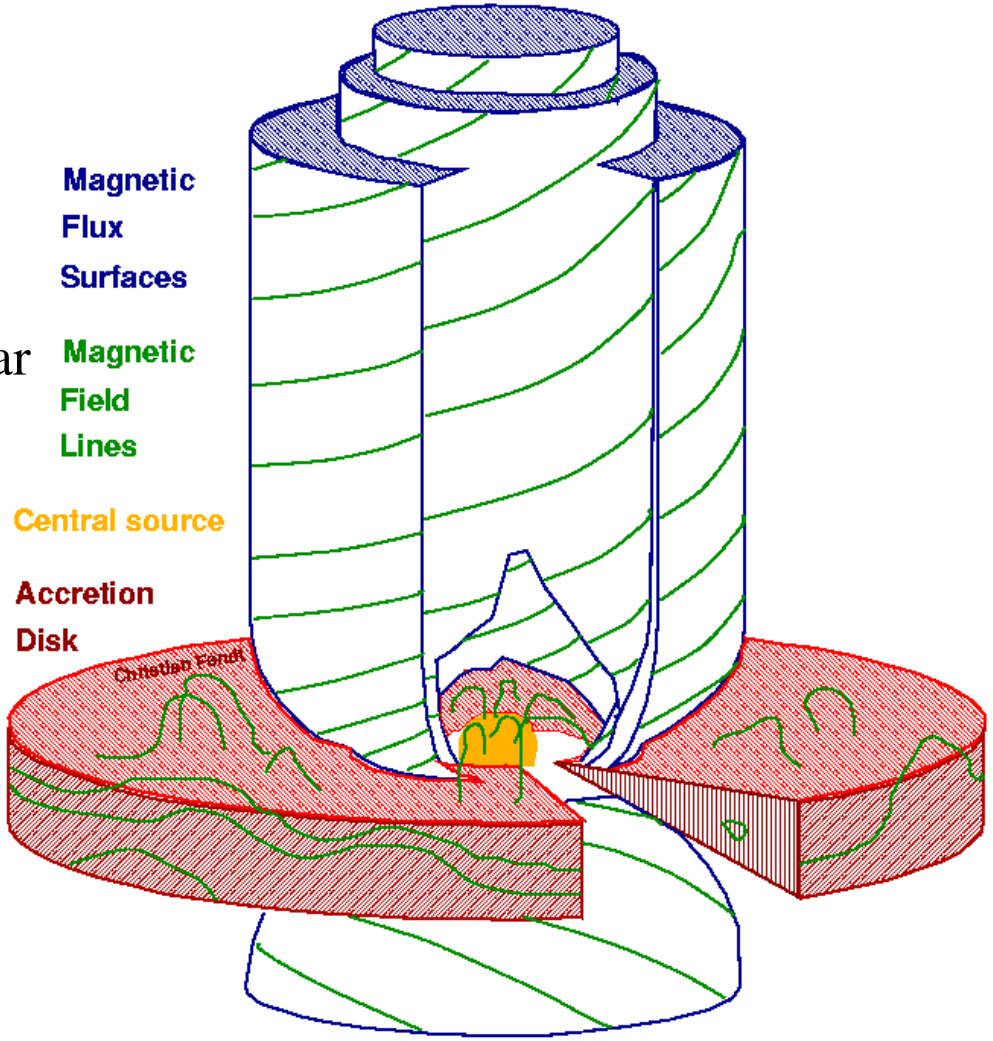
Facts (we know) to remember:

The standard model of jet formation:

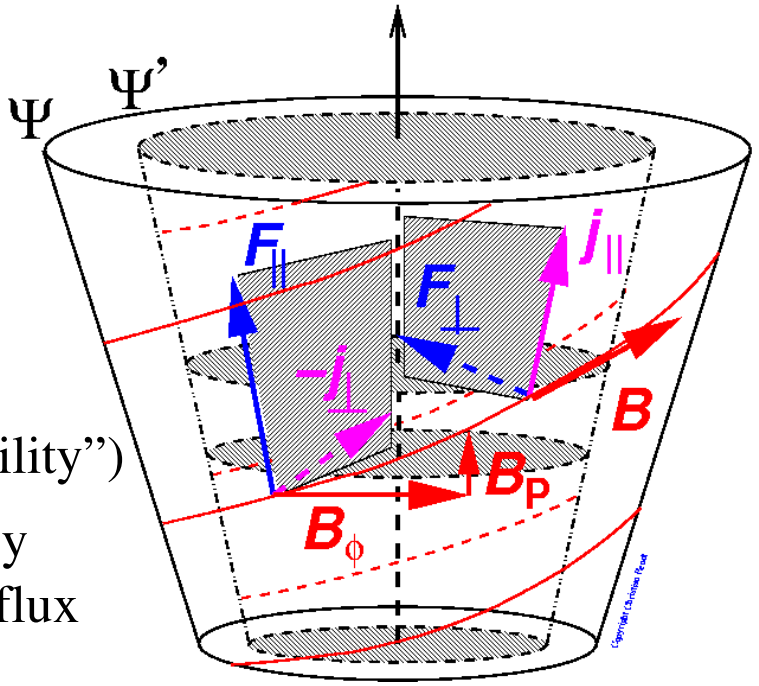
-> jets are collimated disk/stellar winds,
launched / accelerated / collimated
by electro-magnetic forces

-> 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



Summary of lecture – theory part



Facts (we know) to remember:

- jet acceleration: MHD process

  -> initial acceleration: magnetocentrifugal forces ("instability")

  -> energy conversion: magnetic energy -> kinetic energy

  Poynting flux -> kinetic energy flux

  -> force-balance MHD Lorentz force:

  $\boldsymbol{F} \sim \boldsymbol{j} \times \boldsymbol{B}$; parallel component; $\boldsymbol{B}_\phi$ essential

  -> jets start magnetically dominated, end up in ~ energy equipartition

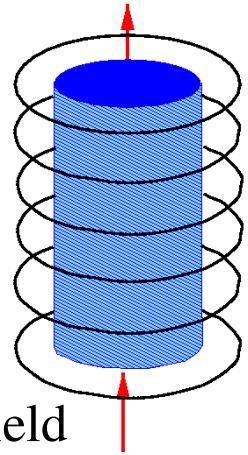
- jet (self-) collimation:

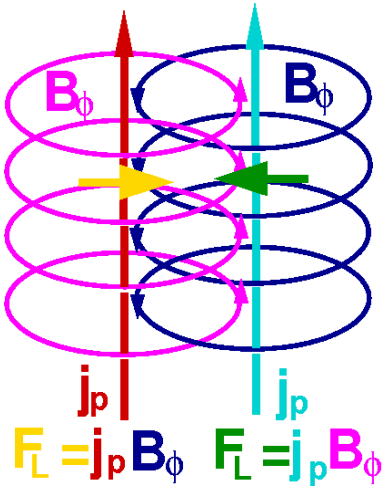
  self-generated toroidal field by plasma inertial forces

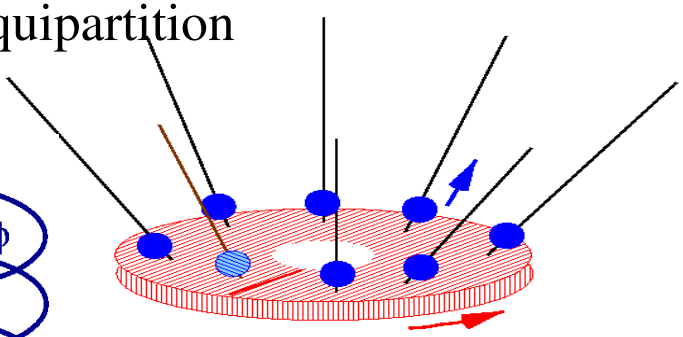
  -> MHD Lorentz force, perpendicular component

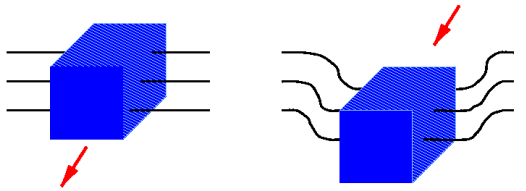
  -> inward tension of toroidal field

  -> numerically approved



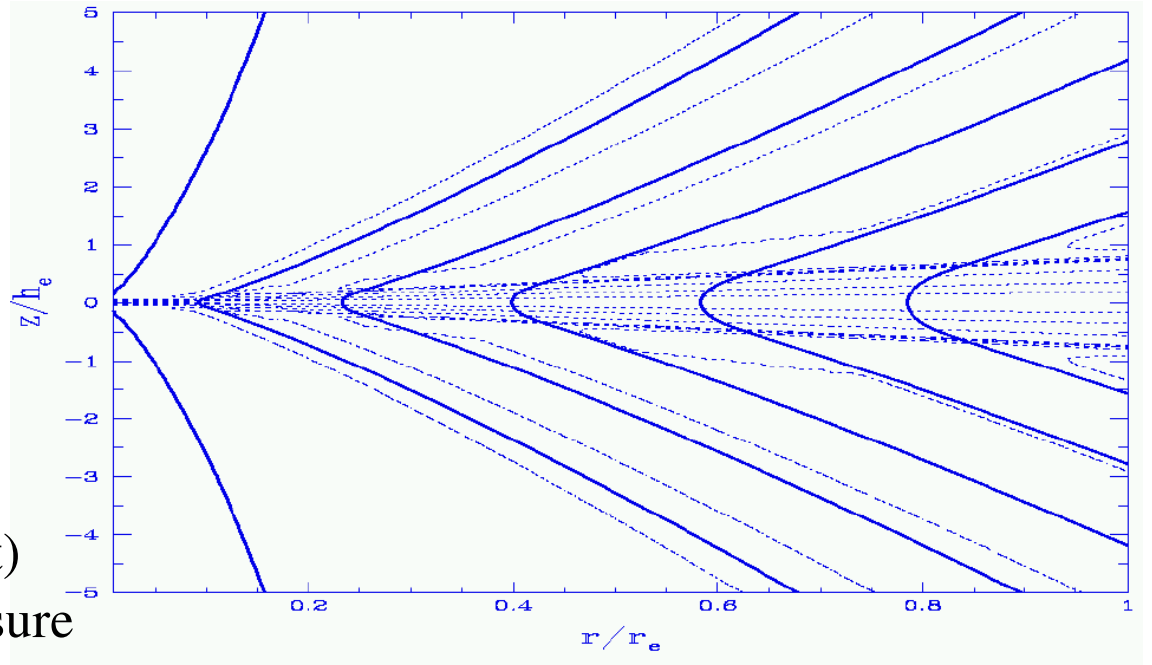






- MHD concept: **ionized, neutral, single fluid**: averaged quantities, $\rho, \boldsymbol{v}, \boldsymbol{j}$.

Summary of lecture – theory part



(Ferreira et al 1995-1997)

Facts (we know) to remember:

- jet launching: MHD process

-> disk wind models:

2 cases (weak field & strong field limit)

$F_{\perp}$ vertically decreases -> gas pressure gradient lifts plasma from disk surface

F_{ϕ} vertically increases -> radial centrifugal acceleration

-> stellar magnetosphere models:

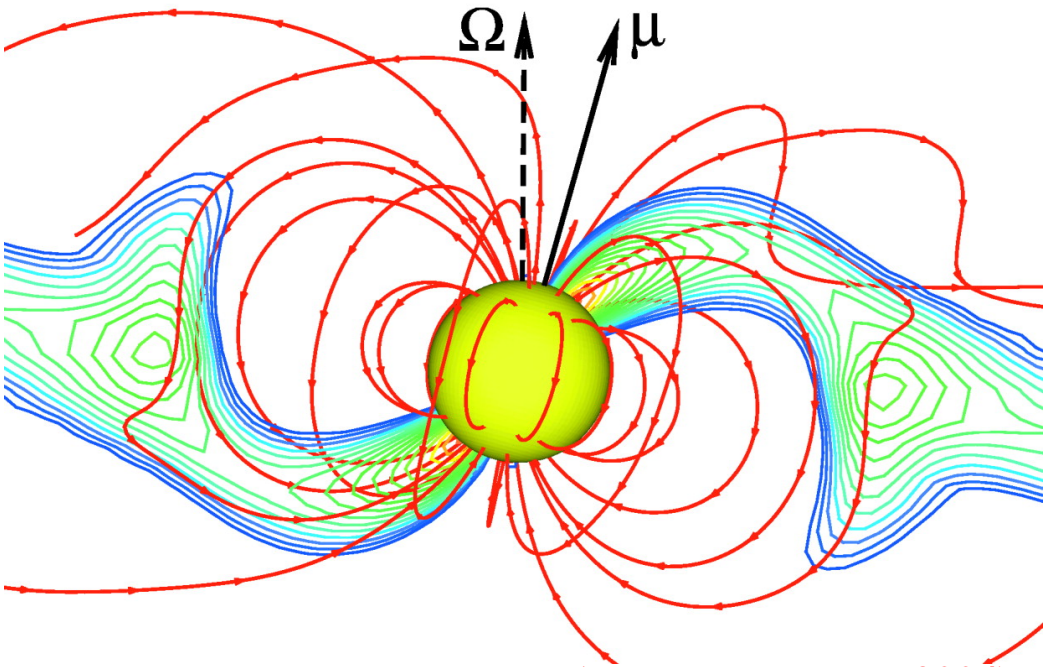
-> disk truncation

-> corotation radius: devides possible infall / ouflow

-> dipole does not survive on large scales

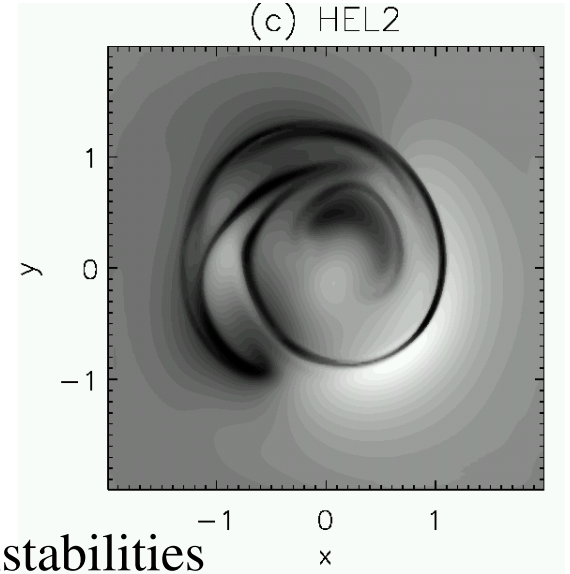
-> dipolar accretion, hot spots / rings

-> so far no collimated outflows found in stellar magnetosphere simulations



(Romanova et al. 2004)

Summary of lecture – theory part

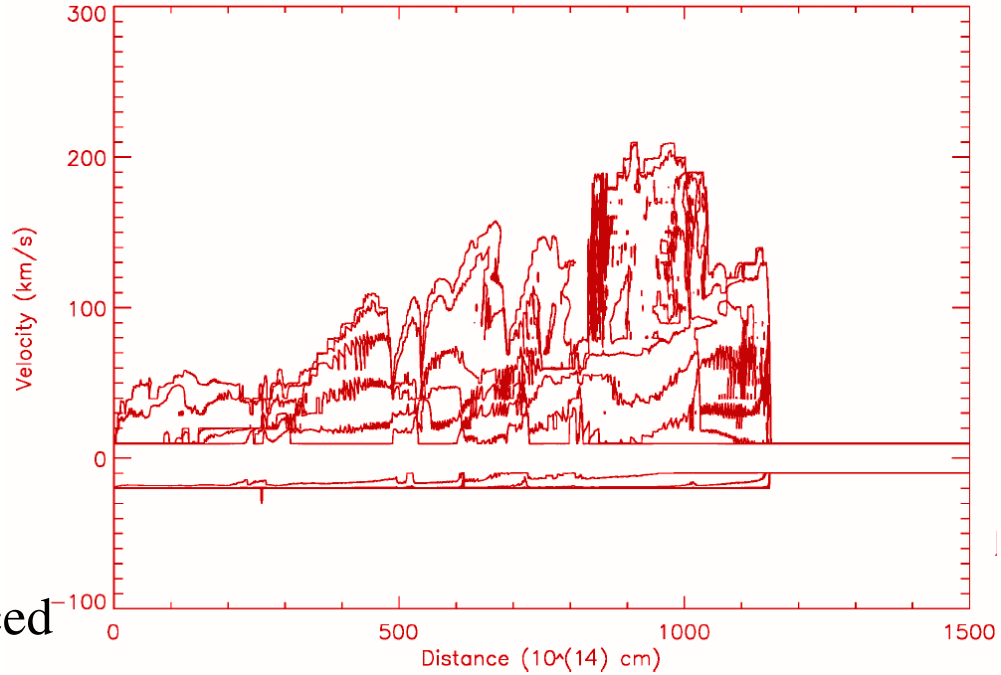


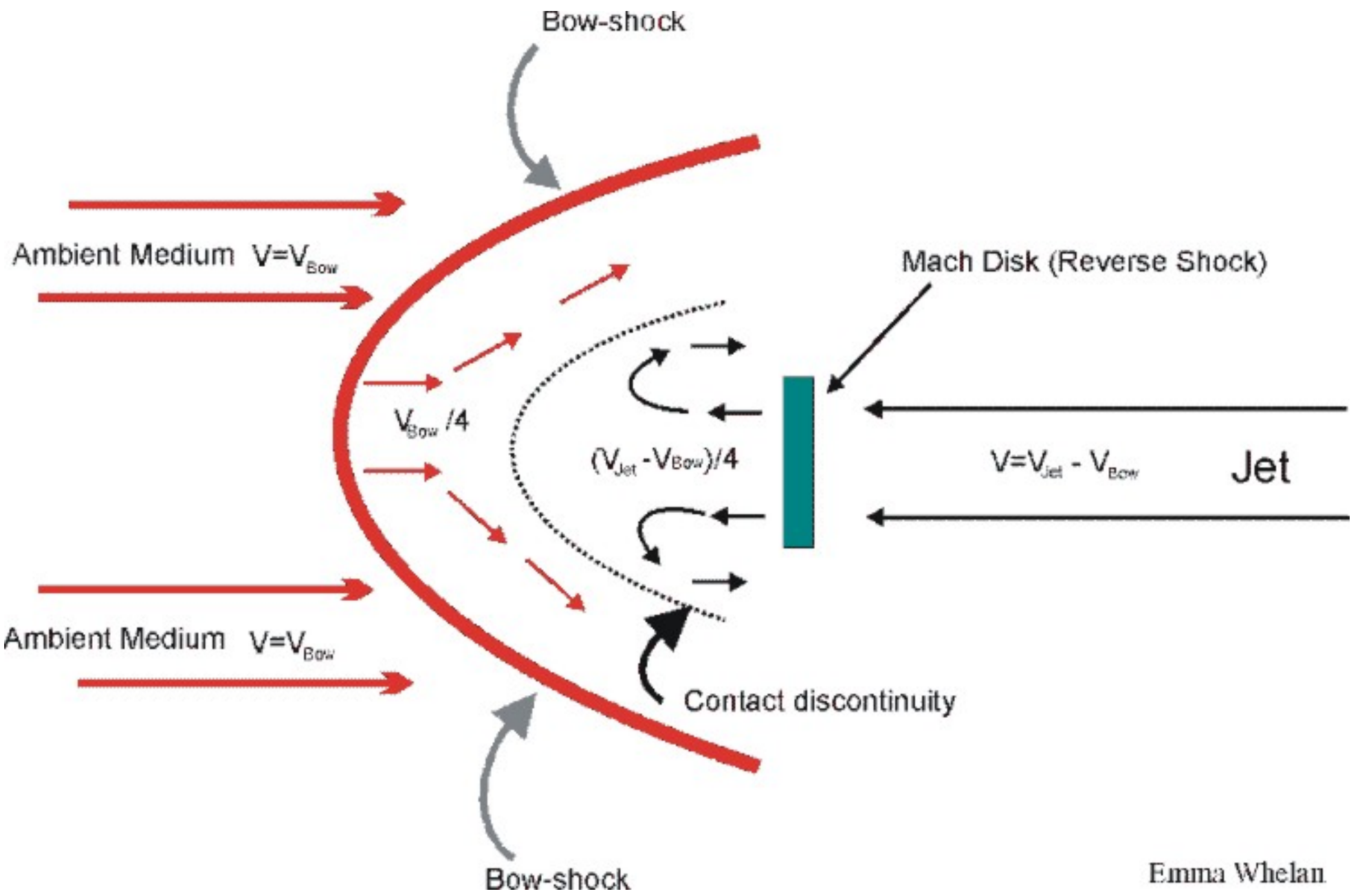
Facts (we know) to remember:

- jet instability:
  - -> magnetic jets more stable than un-magnetized jets
  - -> various instability types & modes excited in jets: sausage, kink, 2nd order, Kelvin-Helmholtz, current-driven, pressure-driven instabilities
  - -> observed jets amazingly stable compared to theoretical jets

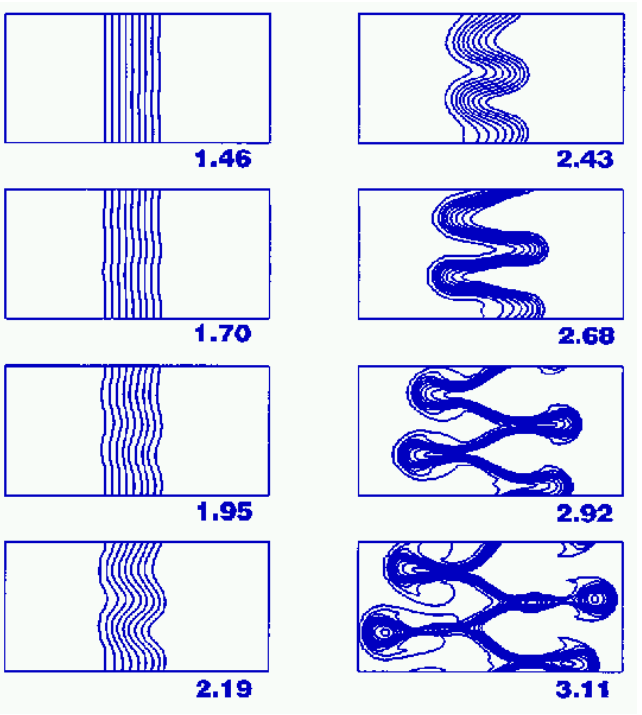
- jet shocks:
  - -> bow shocks, Mach shocks, internal shocks
  - -> Rankine-Hugeniot jump conditions: from conservation laws
  - -> shock excited, optically thin forbidden emission lines in YSO jets
  - -> different physical types: J-shock ("jump"), C-shocks ("contineous", magnetic)

- jet <--> outflows:
  - -> "momentum driven" outflows feasible by energy / time scale arguments
  - -> C-shocks would allow for "soft" energy transfer from jet to outflow
  - -> "Hubble law" for outflow velocity reproduced




Bow-shock
Ambient Medium V=V_Bow
Mach Disk (Reverse Shock)
V_Bow /4
(V_Jet -V_Bow)/4
V=V_Jet - V_Bow
Jet
Ambient Medium V=V_Bow
Contact discontinuity
Bow-shock
Emma Whelan

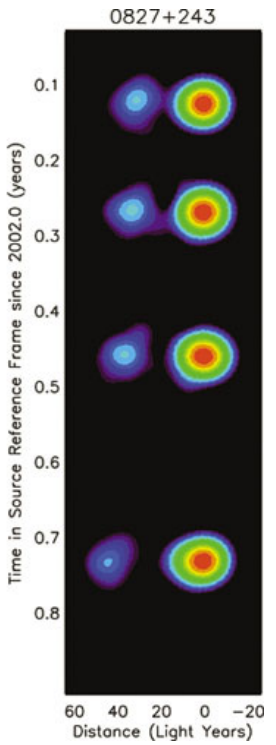
Summary of lecture – theory part



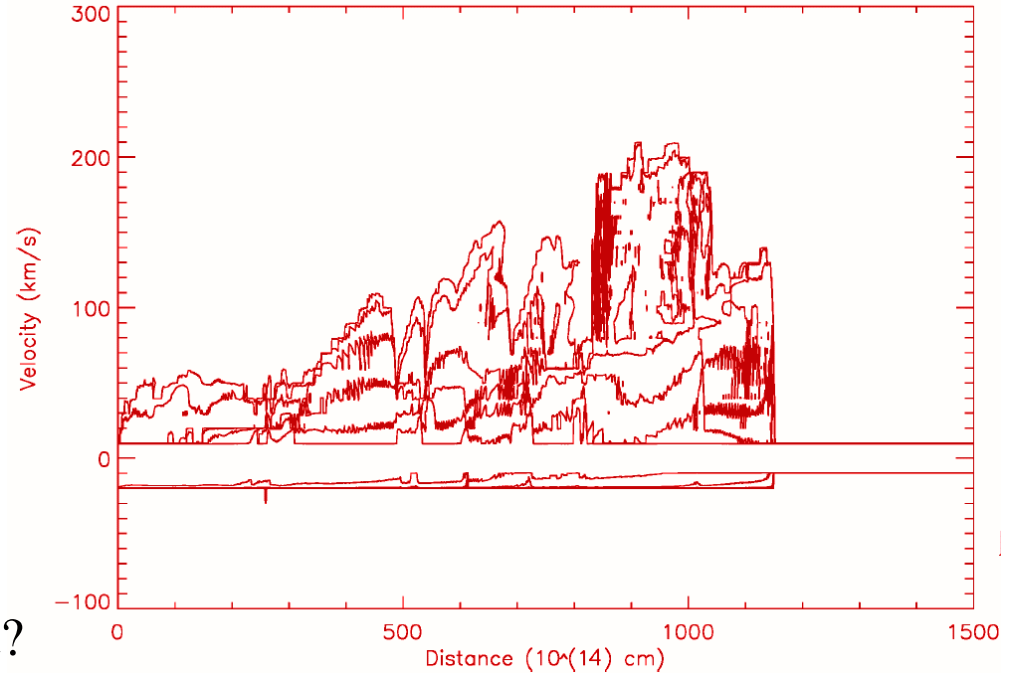
Facts (we know) to remember:

- accretion disks:
  - -> turbulence allows for angular momentum outward transport, thus allowing for accretion
  - -> a-parametrisation for disk turbulence
  - -> magneto-rotational instability creates turbulence
  - -> ADAF: advection dominated acc. disk (some AGN)

- relativistic jets:
  - -> components: core, jets, cocoon, hot spots, lobes
  - -> bulk Lorentz factor $\Gamma \sim 10$, particle Lorentz factor $\gamma \sim 10^3$ -- 10^8
  - -> synchrotron radiation (mostly in radio, some also in optical)
    - -> magnetic field structure / strength -> comptonization
  - -> boosting of radiative power, beaming of radiation cone
  - -> apparent superluminal motion for highly relativistic jets
  - -> launched by black hole (M,J) plus surrounding accretion disk (Blandford & Payne - Blandford & Znajek)
  - -> need very strong magnetic field
  - -> AGN jets <--> micro quasars



Summary of lecture – theory part



Facts (we do not know) to remember:
(facts we would like to know)

- jet – outflow interaction:
  -> protostellar jets over- / underdense?
  -> acceleration mechanism of molecular outflow gas
  -> Hubble / M-v profile real or apparent effect?

- star-disk interaction: "disk-locking" :
  -> angular momentum transfer between star & disk; stellar rotational evolution
  -> so far no collimated outflows found in stellar magnetosphere simulations

- jet stability: not yet explained by theoretical models, all instabilities known (and must be present !!) are developing too fast

- relativistic jets:
  -> matter content: electron-positron (plus magnetic field): pair production + annihilation
  electron-ion (plus magnetic field)
  -> spectral energy distribution in high energy range (synchrotron, self-compton)
  -> jet collimation: in relativistic MHD strong electric field -> decollimating
  -> AGN feedback on cooloing flow of galaxy clusters
  -> two classes: FR-I "lobe-dominated", FR-II "core-dominated": intrinsically different ?

Outlook from lecture – theory part

Progress expected in near future:

Physical concepts exist since "decades", seem to work, numerical proof is partly missing

Needed: simulations, simulations, **simulations ....**

-> larger grid scale, longer time scale

-> problem of asymptotic jet initial condition

(jet nozzle, v(r), B(r), ρ(r))

-> simulations of outflow from jet launching point to molecular outflow

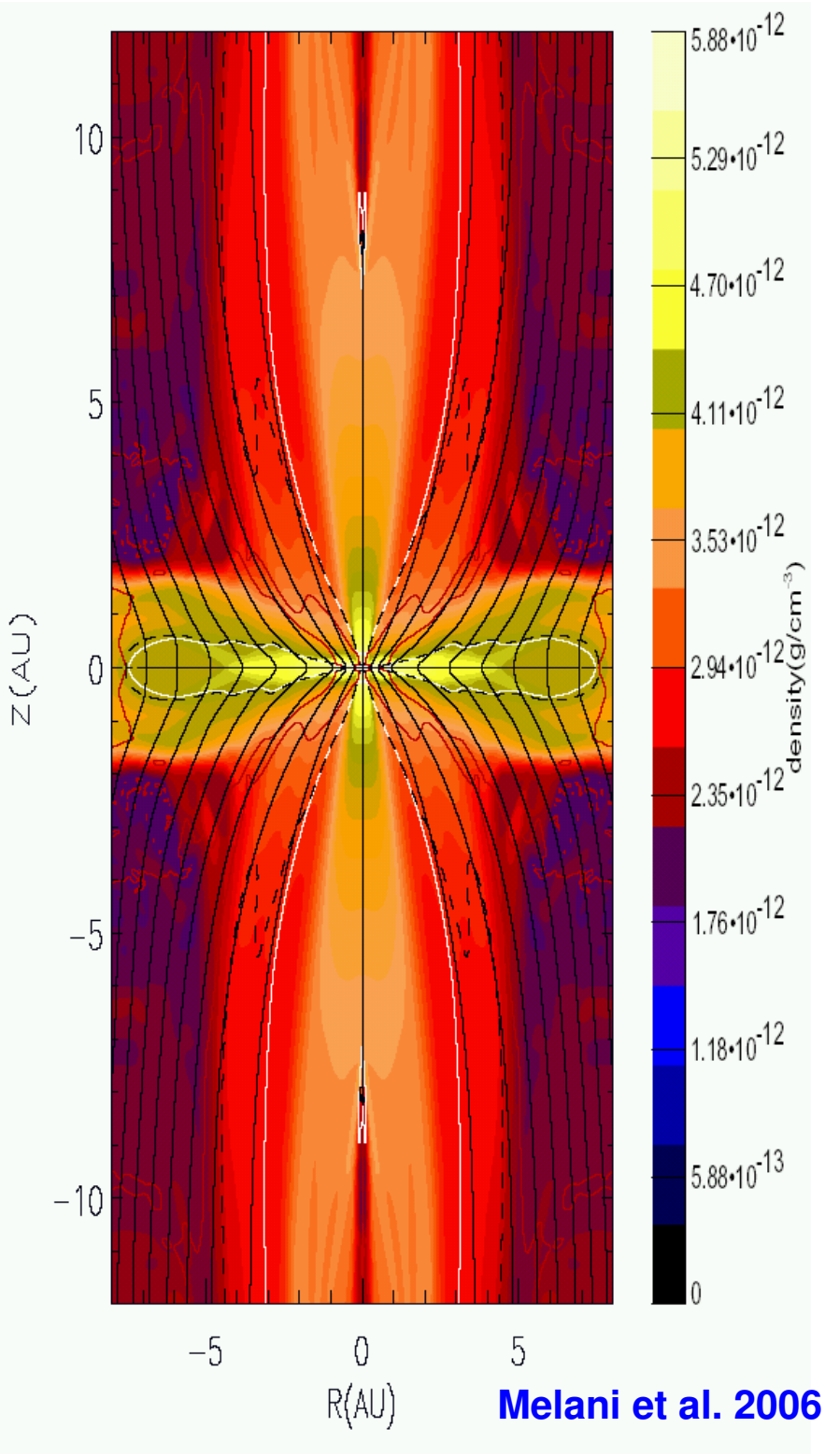
-> more physics included (plus chemistry):

-> orogin of knots unknown so far (missing physical effect??)

-> better disk models incl. radiation transfer, global, multi-fluid, ambipolar-diffusive ...

-> from MHD to emission maps

-> comparison with observations



Melani et al. 2006

Outlook from lecture – theory part

Example of ongoing research:

Rotation and launching region ("X-wind" or disk wind):

-> conservations laws of stationary MHD allow
to trace back along magnetic field lines from
observed region to launching region

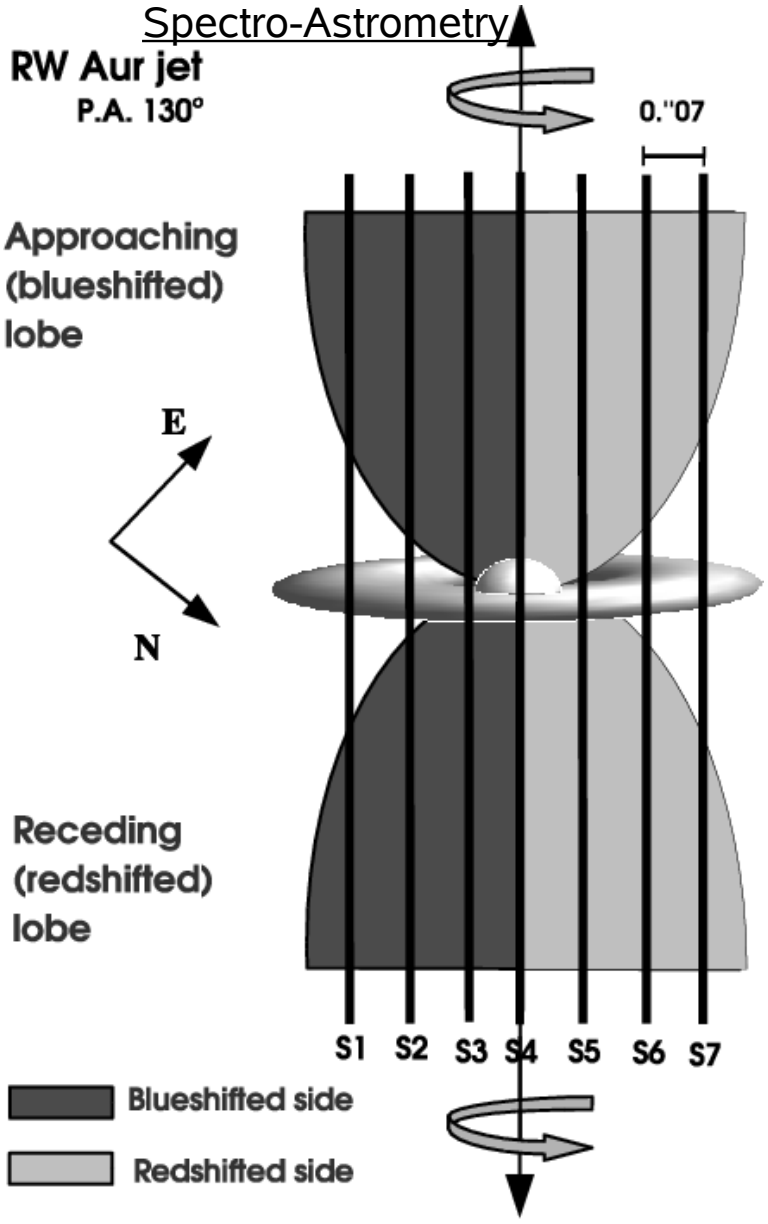
-> strong indication for jet rotation

-> from toroidal & poloidal velocities, footpoints r_0
inferred, where gas comes from
-> outer r_0 for the blue and red wing are
about 0.4 and 1.6 AU (lower limits)
-> consistent with disk winds
-> about 2/3 of the disk angular momentum
may be carried away by jet

-> powerfull method, to be applied to other
sources

-> evidence for rotation under debate:
observed is not rotation but radial velocities

-> compared to numerical simulations



Woitas et al. 2005

Outlook from lecture – theory part

Progress expected in near future:

Relativistic jets:

-> relativistic MHD codes recently developed (RMHD, GRMHD)
(Hawley et al., McKinney et al., Aloy et al. Nishikawa et al..., Mignone et al)
-> applicable for high Γ, low plasma β (?)
-> applicable for strong gravity (black hole), Kerr metric
-> preliminary result (Hawley & Krolik): "funnel jets" launched very close to BH

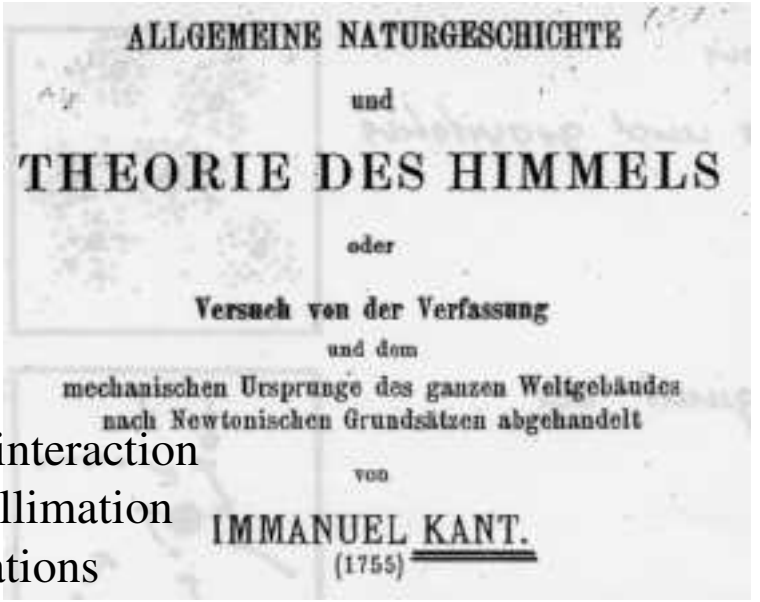
-> non-MHD models
-> 2-component plasma codes following ions + electrons separately
-> electrodynamic codes (~vacuum)

-> radiative RMHD codes: radiation pressure essential in circum-BH disk,
-> thin disk / thick disk (torus), ADAF, neutrino cooling (disks of GRB jets) etc

-> investigate MHD disk wind versus Blandford-Znajek
(or observational answer: jet content, Fe emission lines)
-> jet launching from BH rotational energy ??

-> re-acceleration / re-heating of plasma particles in cocoon / hotspots

Selected further reading – theory part


ALLGEMEINE NATURGESCHICHTE
und
THEORIE DES HIMMELS
oder
Versuch von der Verfassung
und dem
mechanischen Ursprunge des ganzen Weltgebäudes
nach Newtonischen Grundsätzen abgehandelt
von
IMMANUEL KANT.
(1755)

Original papers:

Jets & outflows:

Blandford & Payne 1982: jets as collimating MHD disk winds
Uchida & Shibata 1985: 1st simulations of magnetosphere – disk interaction
Heyvaerts & Norman 1989 : analytical proof of asymptotic jet collimation
Koessl et al. 1990; Stone & Norman 1993: jet propagation simulations
Ouyed & Pudritz 1997: simulations of MHD jet collimation
Ferreira 1997: accretion-ejection models (stationary MHD)
Komissarov 2005: simulations of Blandford-Znajek mechanism

"Stellar wind" models:

Camenzind 1990: stellar magnetosphere – disk interaction and jets
Koenigl 1991: star – disk angular momentum exchange
Shu et al. 1994: "X-wind"
Romanova et al. 2004, 2005: simulations of 2D,3D disk-magnetosphere interaction

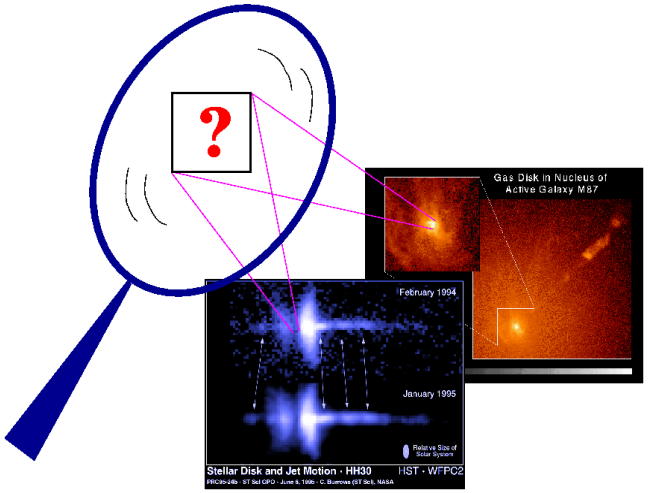
Accretion disks:

Shakura & Sunyaev 1973: α-parametrisation
Balbus & Hawley 1991: magneto-rotational instability as source of disk turbulence

Review articles:

Blandford 1990: Saas-Fee lecture course: physical processes in AGN jets
Pudritz et al. 2007: Protostars & Planets V review article on jet theory/simulations

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: forbidden emission lines (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.)


Thank you
for your interest & patience !!
Christian Fendt