From YSOs to AGNs:

Relativistic Jets in Context

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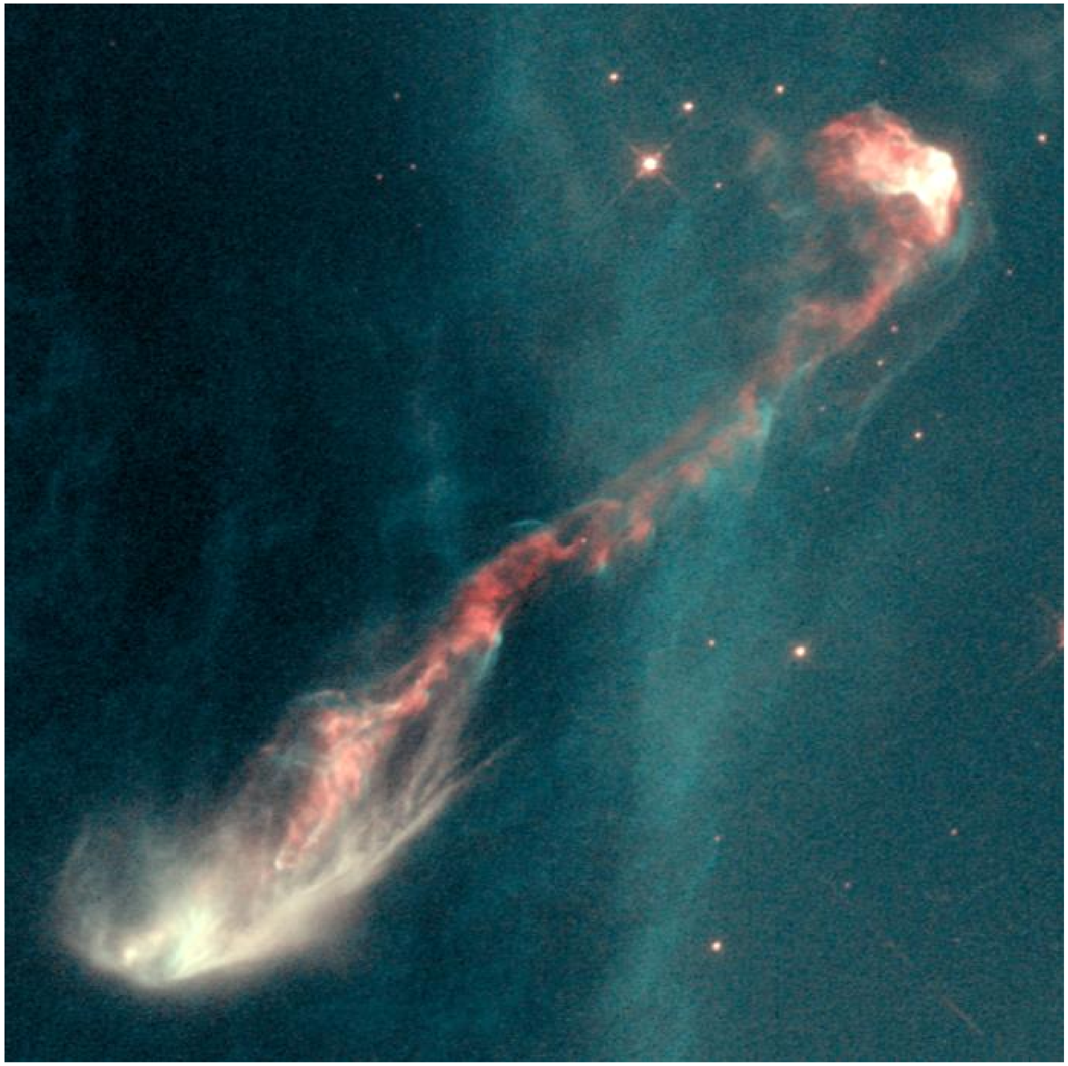
Outline:

- Jets from Young Stellar Objects (YSOs)
- Origin of outflows: disk vs. central object
- Origin of magnetic field: flux transport in disks
- Dusty disk outflows
- The accretion–outflow connection: “fundamental plane” of accreting objects
- Concluding remarks

YSO Jets



Bipolar outflows and jets

- Bipolar molecular outflows and narrow atomic (but sometimes also molecular) jets are ubiquitous phenomena in protostars (about 1000 collimated outflows of all sorts are now known).

  The bipolar lobes are generally understood to represent ambient molecular material that has been swept up by the much faster, highly supersonic jets that emanate from the central star/disk system.

- Jets associated with low-luminosity ($L_{\rm bol} < 10^3 L_\odot$) YSOs have velocities in the range $\sim 150 - 400~{\rm km~s^{-1}}$, large ($> 20$) Mach numbers, and inferred mass outflow rates $\sim 10^{-9} - 10^{-7}~M_\odot~{\rm yr}^{-1}$. They are collimated on scales of a few 10s of AU, and exhibit opening angles as small as $\sim 3 - 5^\circ$ on scales of $10^3 - 10^4~{\rm AU}$.

  High-resolution observations of optically visible jets from classical T Tauri stars reveal an onion-like morphology, with the regions closer to the axis having higher velocities and excitations and appearing to be more collimated.

Detailed optical/NIR spectral diagnostic techniques have been developed and applied to classical (Herbig-Haro) protostellar jets, making it possible to directly estimate the neutral densities in the forbidden-line emission regions.

- Outflows have also been detected by optical observations of intermediate-mass ($2 \lessapprox M_*/M_\odot \lesssim 10$) Herbig Ae/Be stars and other high-luminosity sources. The jet speeds and mass outflow rates in these YSOs are larger by a factor $\sim 2-3$ and $\sim 10-100$, respectively, than in the low-$L_{\rm bol}$ objects.

Connection with accretion disks

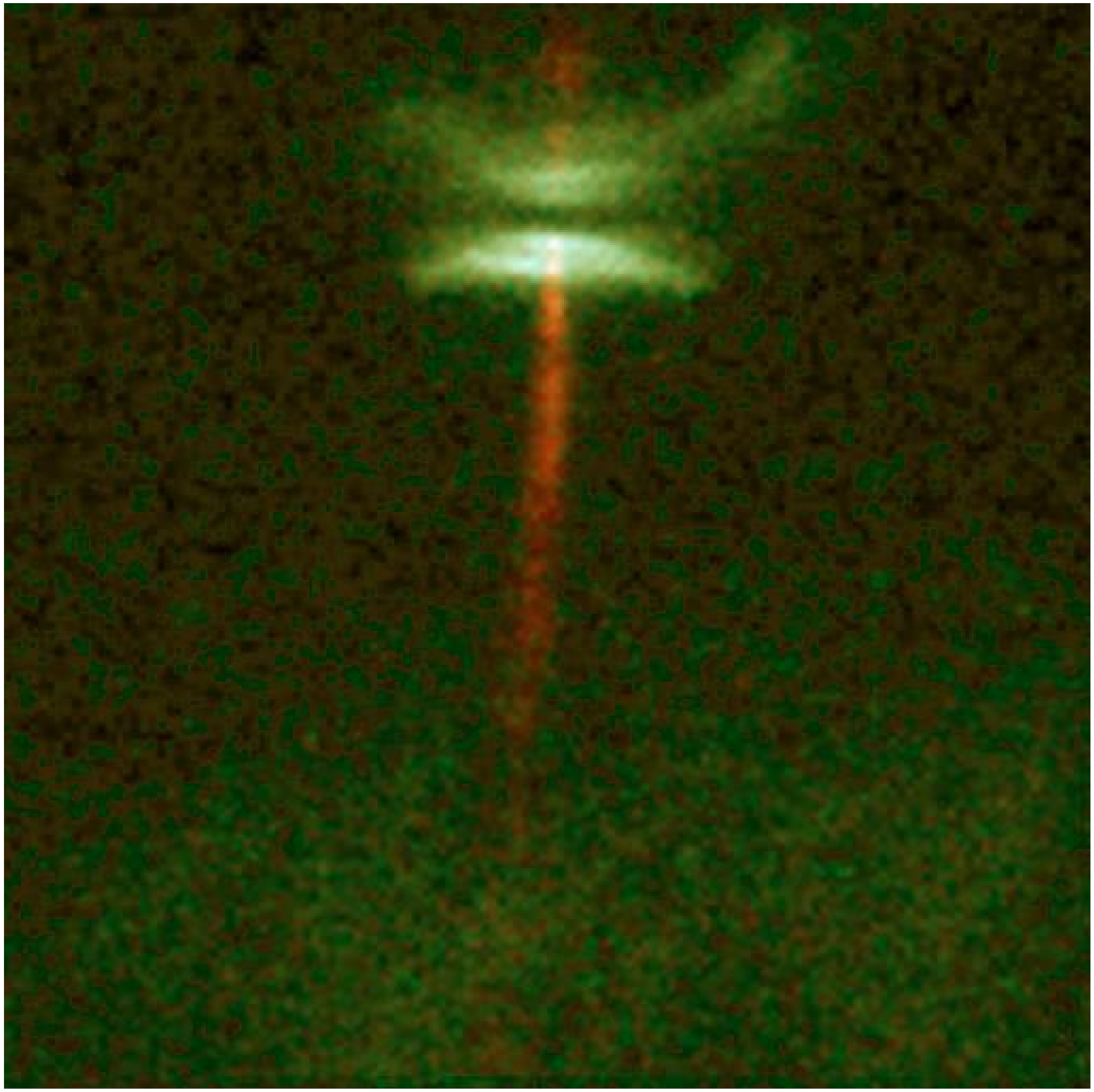
- Strong correlations are found between the presence of outflow signatures (P-Cygni line profiles, forbidden line emission, thermal radio radiation, well-developed molecular lobes) and accretion diagnostics (UV, IR, and mm emission excesses, inverse P-cygni line profiles) in T Tauri stars.

- Apparent decline in outflow activity with stellar age follows a similar trend exhibited by disk frequency and inferred mass accretion rate.

- The correlations between accretion and outflow signatures extend smoothly to YSOs with masses of $\sim 10\ M_\odot$.

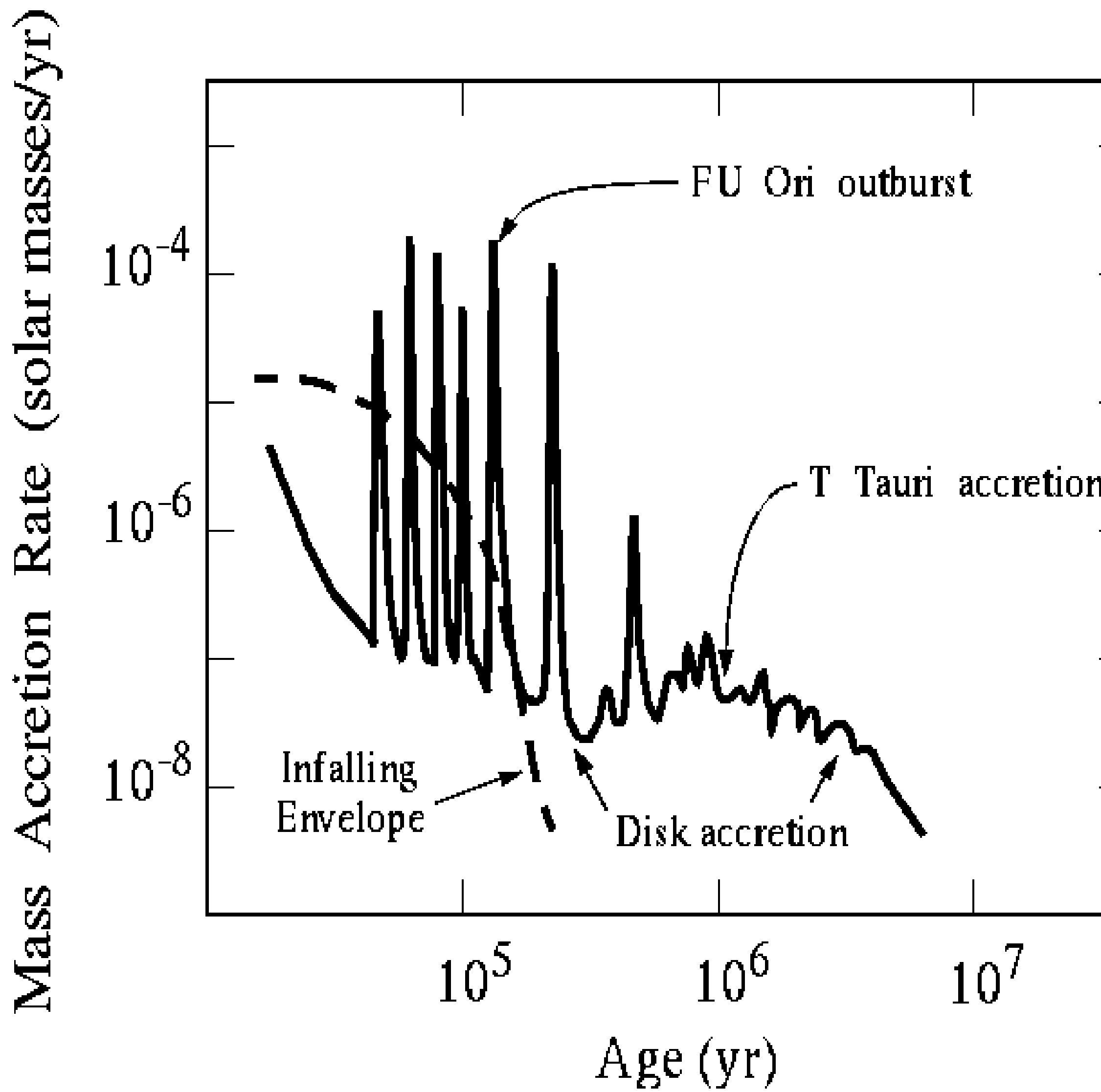
♣ These results strongly suggest that outflows are powered by accretion and that the same basic physical mechanism operates in both low- (down to nearly the planetary-mass limit) and intermediate- (but possibly also high-) mass YSOs.

- Accretion disks have been detected by means of high spatial- and spectral-resolution interferometric observations in sub-mm, mm, MIR, and NIR.



The disks appear to be rotationally supported (for $r \lesssim 100$ AU); when the rotation law can be determined, it is usually consistent with being Keplerian ($V_\phi \propto r^{-1/2}$). The most recent data indicate that $M_{\rm disk} \lesssim M_*$ at least up to $M_* \sim 20\ M_\odot$.

- Accretion and outflow occur in both a steady and nonsteady fashion. In particular, most of the mass of low-mass stars is evidently assembled during repetitive rapid accretion events (each lasting $\sim 10^2$ yr, with $\dot{M}_{\rm in} \sim 10^{-4}\ M_\odot\ {\rm yr}^{-1}$) that correspond to FU Orionis outbursts.



Calvet, Hartmann, & Strom (2000)

Disk vs. Central Object

- Astrophysical jets on all scales are inferred to be driven electro- or hydro-magnetically through the tapping of the rotational kinetic energy of the accretion disk or the central object.

This inference is particularly strong in the case of YSOs, where direct measurements of the momentum discharge ($\dot{M}V$) into the bipolar lobes indicate that $\dot{M}_{\rm jet}V_{\rm jet} \sim 10^2 - 10^3\, L_{\rm bol}/c$.

- The question of the relative contribution of the disk and the central object is still being debated for all jet sources.

- In the case of AGNs and GRBs, electromagnetic extraction of the spin energy of the central black hole (BH) through a disk-supported magnetic field was proposed as the origin of the relativistic jets in these sources (e.g., Blandford 2002; Lyutikov 2006; Tchekhovskoy, Narayan, & McKinney 2010).

Questions have, however, been raised, both theoretically (e.g., Ghosh & Abramowicz 1997; Livio, Ogilvie, & Pringle 1999) and observationally (e.g., Cao & Rawlings 2004), about whether a BH-driven jet outflow would dominate over a disk outflow.

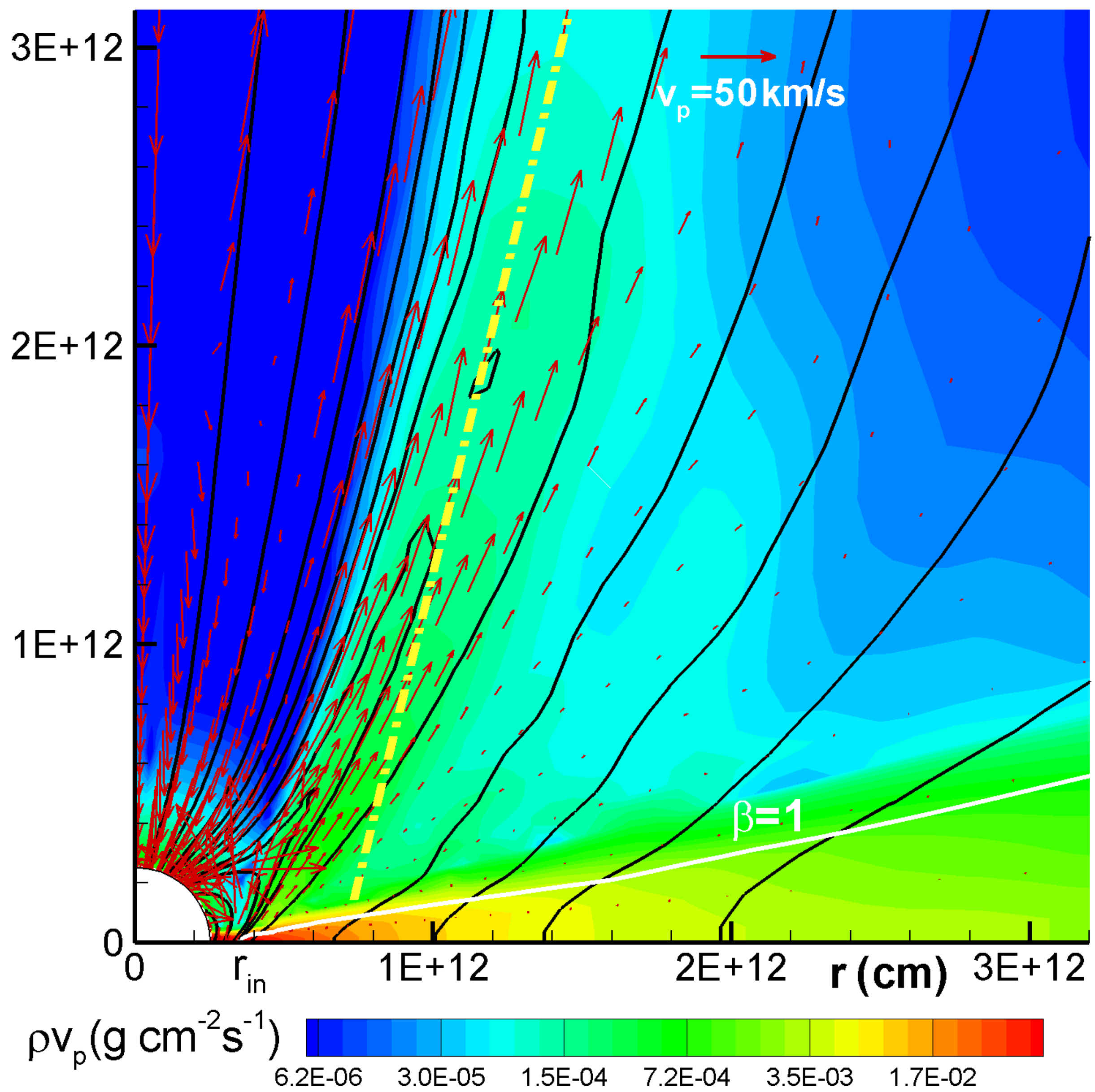
- In the case of Galactic X-ray binaries (XRBs), the inferred similarity between black hole- and neutron star-driven relativistic jets has been used to argue that the jet launching mechanism is an intrinsic feature of the accretion flow and does not depend strongly on the nature of the central object (e.g., Migliari & Fender 2006; Körding, Fender, & Migliari 2006; Soleri & Fender 2011; Migliari, Miller-Jones, & Russell 2011).

- For YSOs, most models envision a centrifugally driven wind of accreted matter. What is debated is whether the wind is launched from the stellar surface or its vicinity by the stellar magnetic field (e.g., Shu et al. 2000; Matt & Pudritz 2008; Cranmer 2008), or whether it originates further out in the disk and involves the interstellar magnetic field (e.g., Königl & Pudritz 2000).

- A promising testing ground is provided by FU Orionis systems.

- Based on evidence that the continuum emission in FU Ori outbursts originates in a circumstellar disk and on the detection of moderately blueshifted, intermediate-strength optical absorption lines in FU Ori, Calvet, hartmann, & Kenyon (1993) argued that the powerful outflows in these systems represent disk winds launched relatively far away from the stellar surface.

- Recent numerical simulations have, however, indicated that an interpretation in terms of a conical wind, which arises from the interaction of the accretion flow with the stellar magnetosphere, could potentially also explain the observations (Königl, Romanova, & Lovelace 2011).



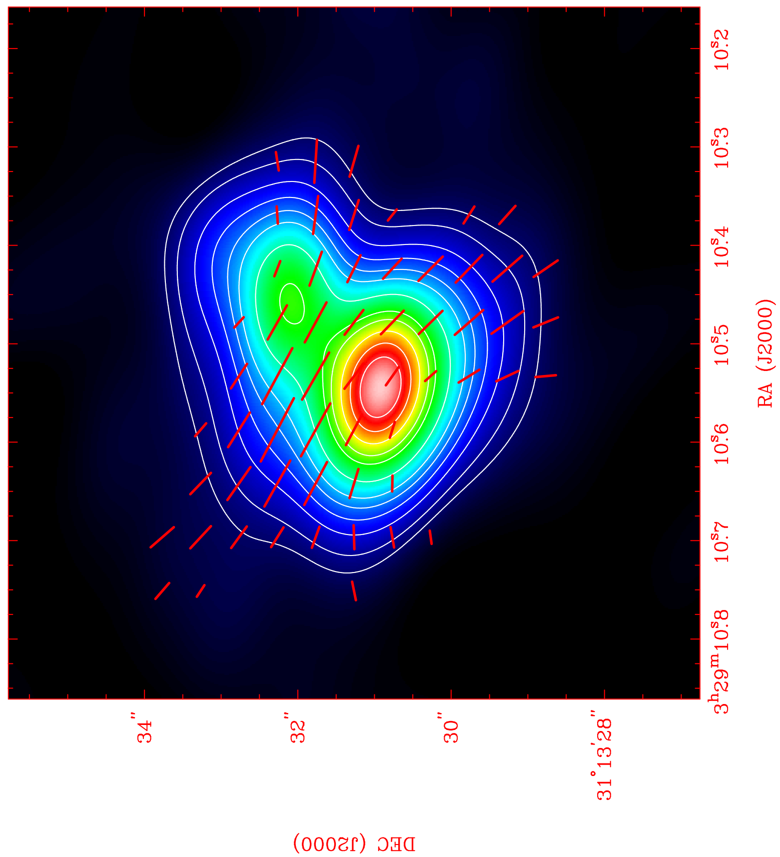
3E+12
2E+12
1E+12
0
0
r_in
1E+12
2E+12
r (cm)
3E+12
v_p=50km/s
β=1
ρv_p(g cm^-2 s^-1)
6.2E-06
3.0E-05
1.5E-04
7.2E-04
3.5E-03
1.7E-02

Magnetic Flux Transport in Disks

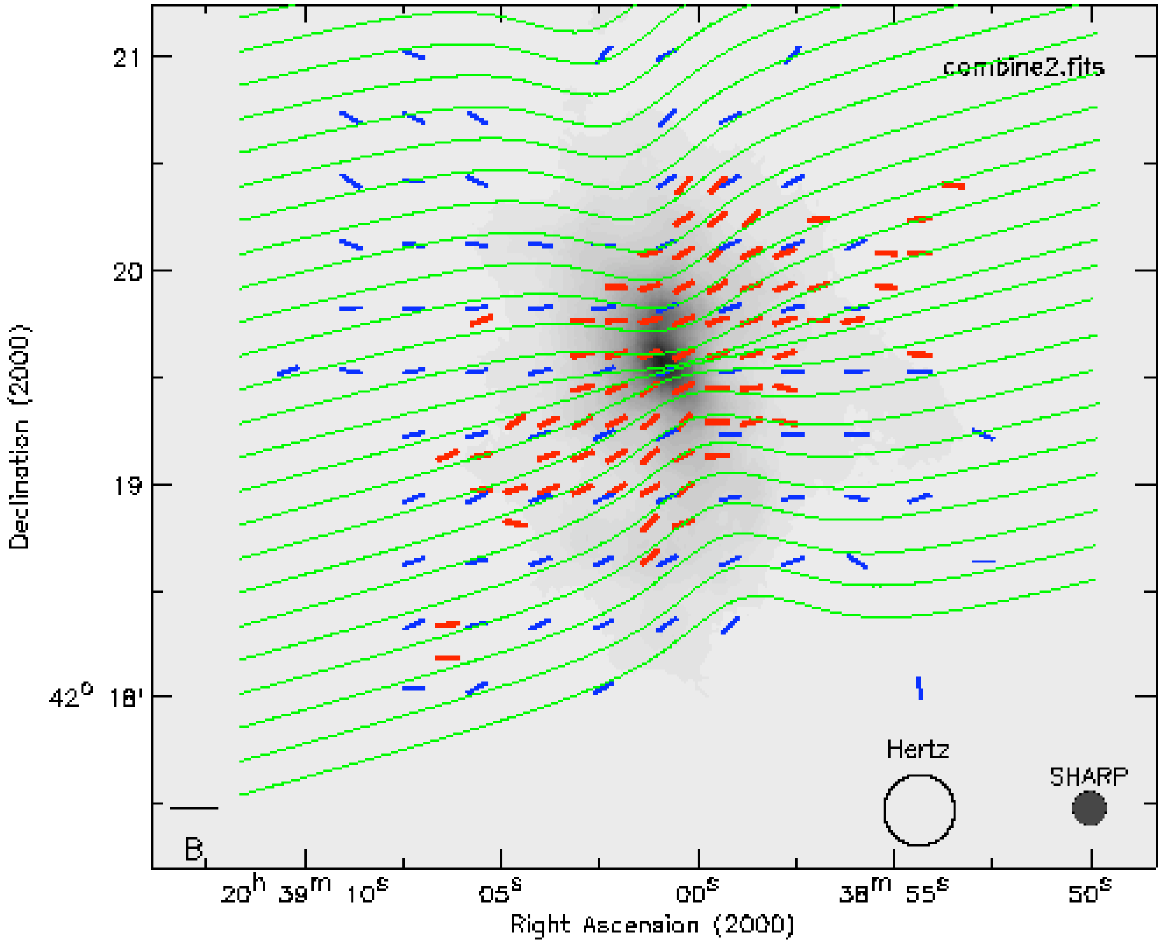
Most jet-driving models envision an ordered, large-scale magnetic field that threads the source.

- In the case of stellar jets, this field could originate in the star (e.g., the "X-wind" YSO model of Shu et al. 1994).
- It could in principle also originate in a disk dynamo.
- Alternatively, the field could be advected inward by the accretion flow. This possibility arises naturally in YSOs, where polarization and Zeeman measurements on sub-pc scales indicate a large-scale interstellar field that is dynamically important in supporting the molecular cloud core before it collapses to form the central star and disk.

NGC 1333 Iras 4A (Girart et al. 2006)



DR21 Main (Kirby 2009)



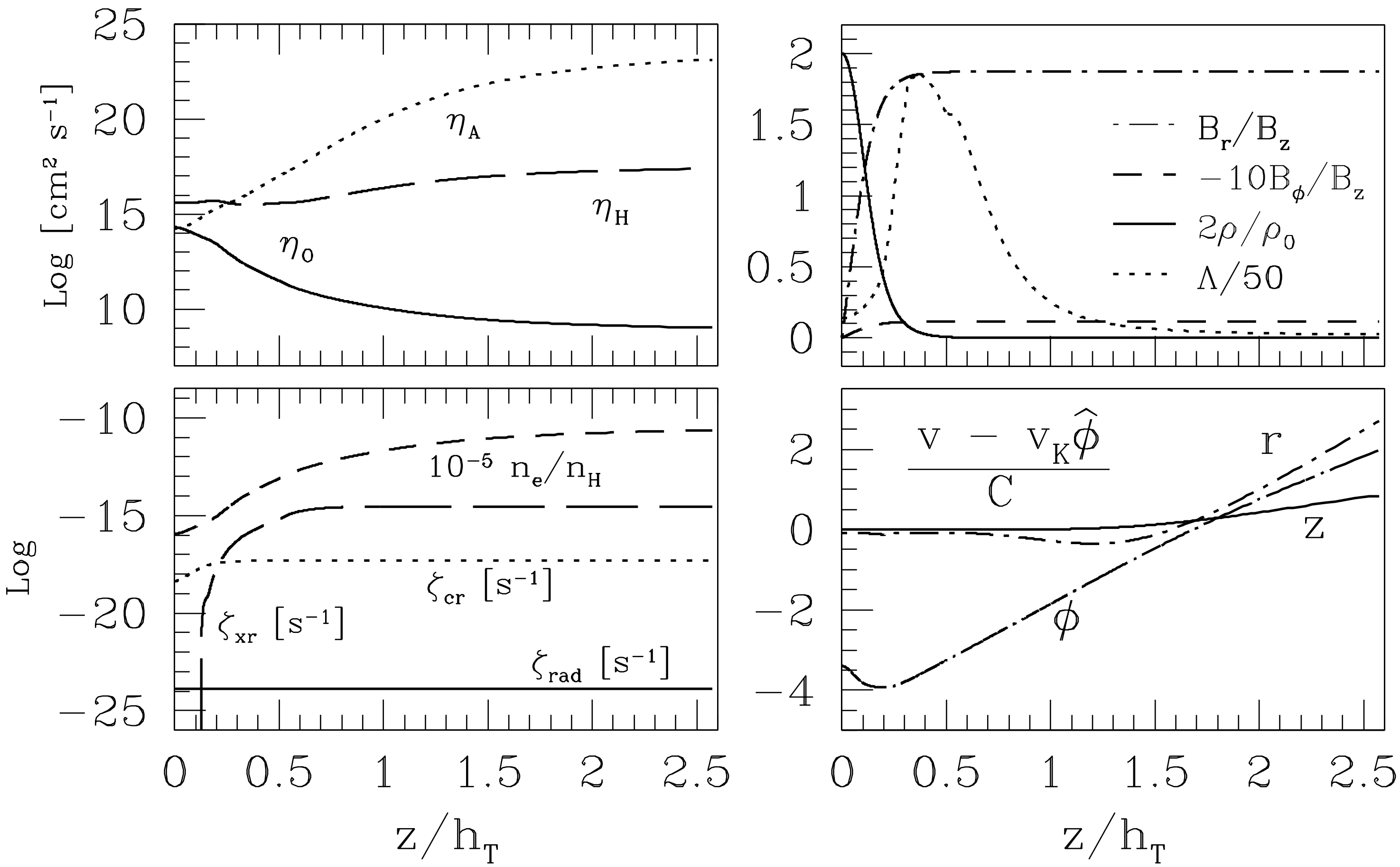
♣ A potential problem arises in disks with turbulent angular momentum transport, since the effective magnetic diffusivity is expected to be comparable to the effective viscosity and would therefore inhibit magnetic flux transport through the disk (Lubow, Papaloizou, & Pringle 1994).

• If the turbulence derives from the magnetorotational instability then it may be possible to overcome this difficulty on account of the expected suppression of this instability in the magnetically dominated surface layers of the disk (Rothstein & Lovelace 2008). A related "coronal mechanism" was found in the global, 3D, GRMHD simulation of Beckwith, Hawley, & Krolik (2009).

- Vertical angular momentum transport through the disk surfaces, either by torsional Alfvén waves (magnetic braking) or by a centrifugally driven wind, offers a straightforward resolution of this potential dilemma by decoupling the angular momentum and flux transport processes.

- In the case of YSO disks, the disk diffusivity can be explicitly calculated for given ionization sources (primarily cosmic rays and X-rays). The bulk of the disk is typically weakly ionized and lies in either the ambipolar, Hall, or Ohm diffusivity regime.

Vertical structure of wind-driving YSO disk at 1 AU

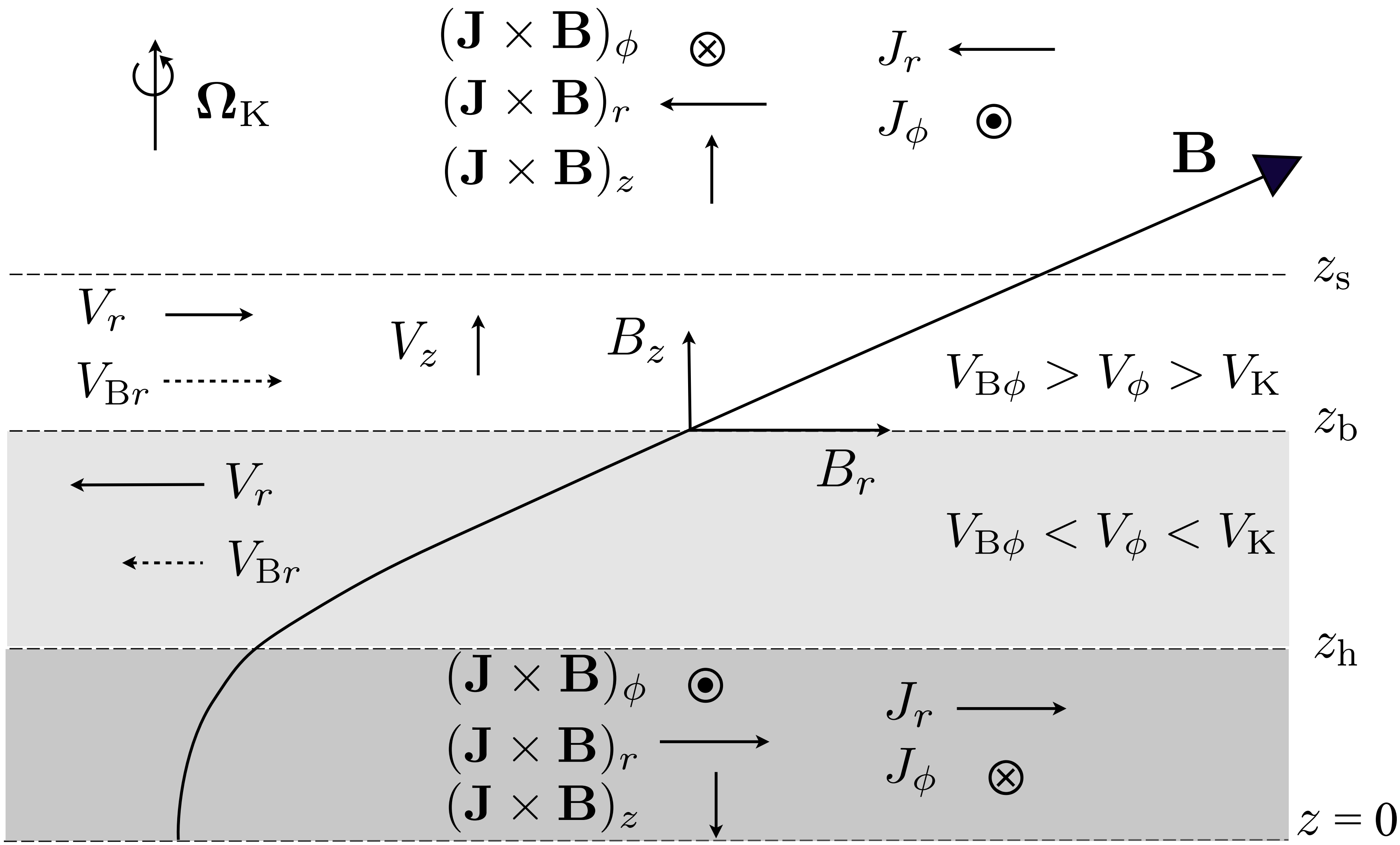


Königl & Salmeron (2011)

Global semi-analytic similarity solutions for disks in the ambipolar diffusivity regime have been constructed assuming either magnetic braking (Krasnopolsky & Königl 2002) or a centrifugally driven wind (Teitler 2011).

♣ These solutions explicitly demonstrate that angular momentum transport along open magnetic field lines that thread the disk enables the inward advection of this field by the accretion flow.

Structure of diffusive, wind-driving MHD disk



Dusty Disk Outflows

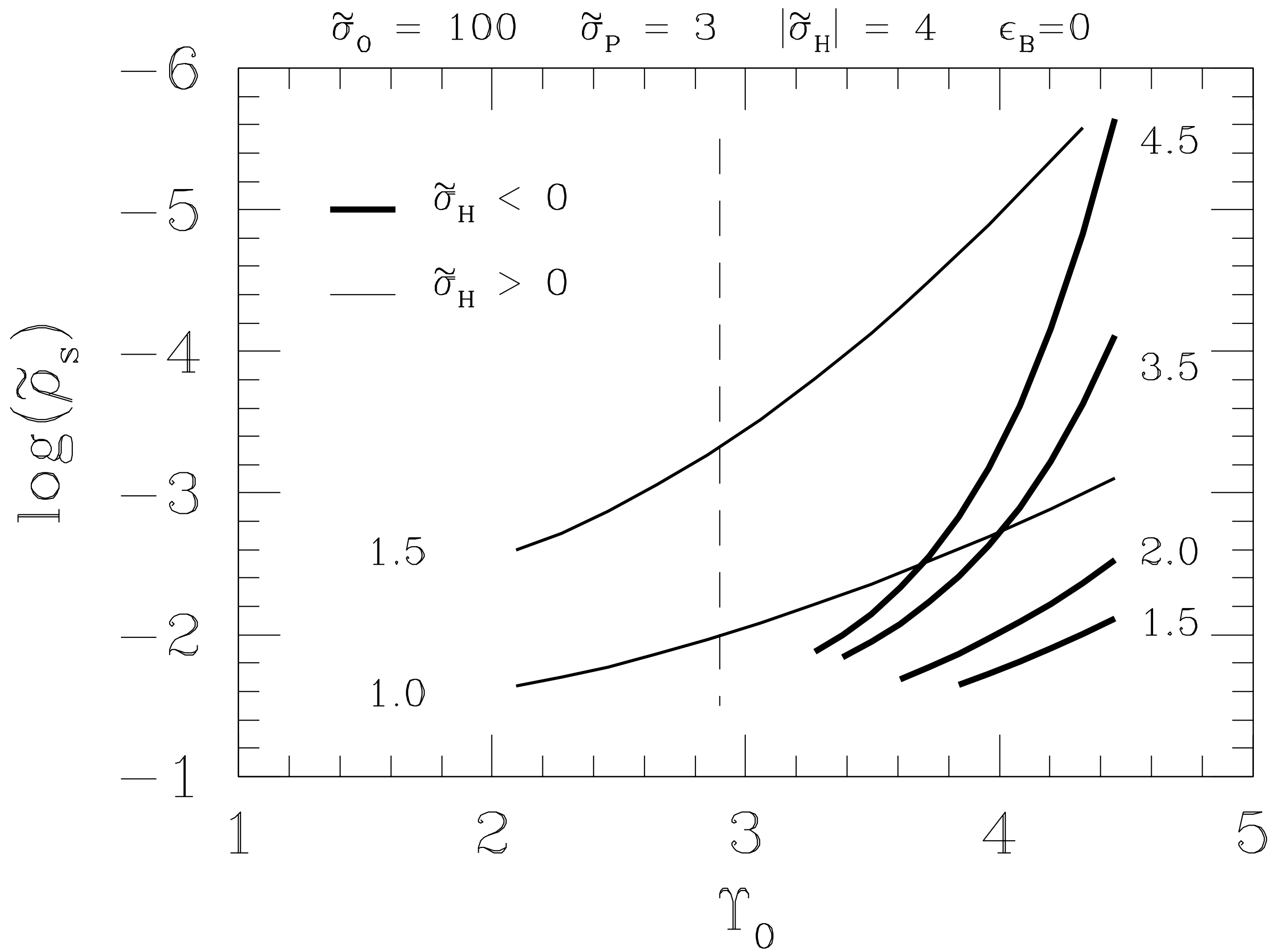
- It is likely, based on observations and numerical simulations, that the outer regions of at least some AGN disks are mostly molecular and dusty. This is manifestly the case in YSO disks.

- Centrifugally driven disk winds may be a crucial ingredient in confining relativistic AGN jets (which is required for their efficient acceleration; e.g., Komissarov et al. 2009) and in collimating them (e.g., Gracia et al. 2009) on scales $\lesssim 0.1$ pc.

- Disk winds originating on these scales could also form the Faraday-rotation “sheaths” around parsec-scale jets (Blandford & Levinson 1995), which are now being identified in FR I sources (e.g., Kharb et al. 2009).

Estimates of the density and magnetic field amplitude in the Faraday sheaths indicate that the corresponding disk winds could originate in disk regions where the Hall diffusivity is dominant. Under these conditions, the Faraday rotation-measure gradients across the jets could exhibit a preferred sense (Königl 2010), as observational data appear to indicate (Contopoulos et al. 2009).

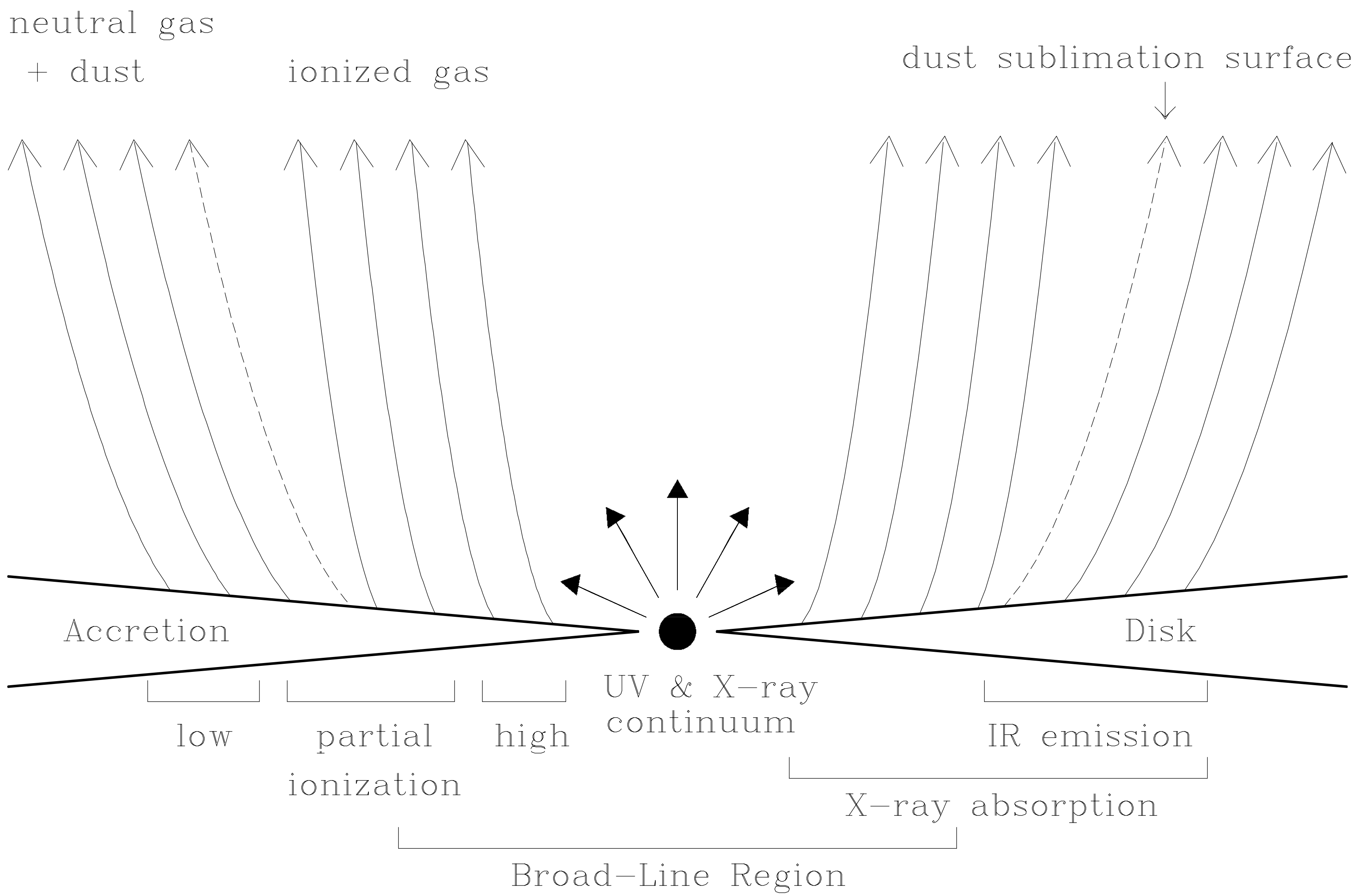
Positive- and negative-polarity solutions in the Hall domain



Salmeron, Königl, & Wardle (2011)

♣ Centrifugally driven winds can readily uplift dust from the disk surfaces (Safier 1993).

• AGN disk winds of this type would have a strongly stratified density profile and would be photoionized in their inner regions and dusty in their outer zones. These configurations can naturally account for the obscuration properties of the "fuzzy" molecular tori that underlie the Type 1/ Type 2 AGN unification scheme as well as for the attenuation characteristics of the partially ionized "warm absorber" component on smaller spatial scales (Königl & Kartje 1994). In addition, this model explains the continuum polarization properties of Seyfert galaxies (Kartje 1995).

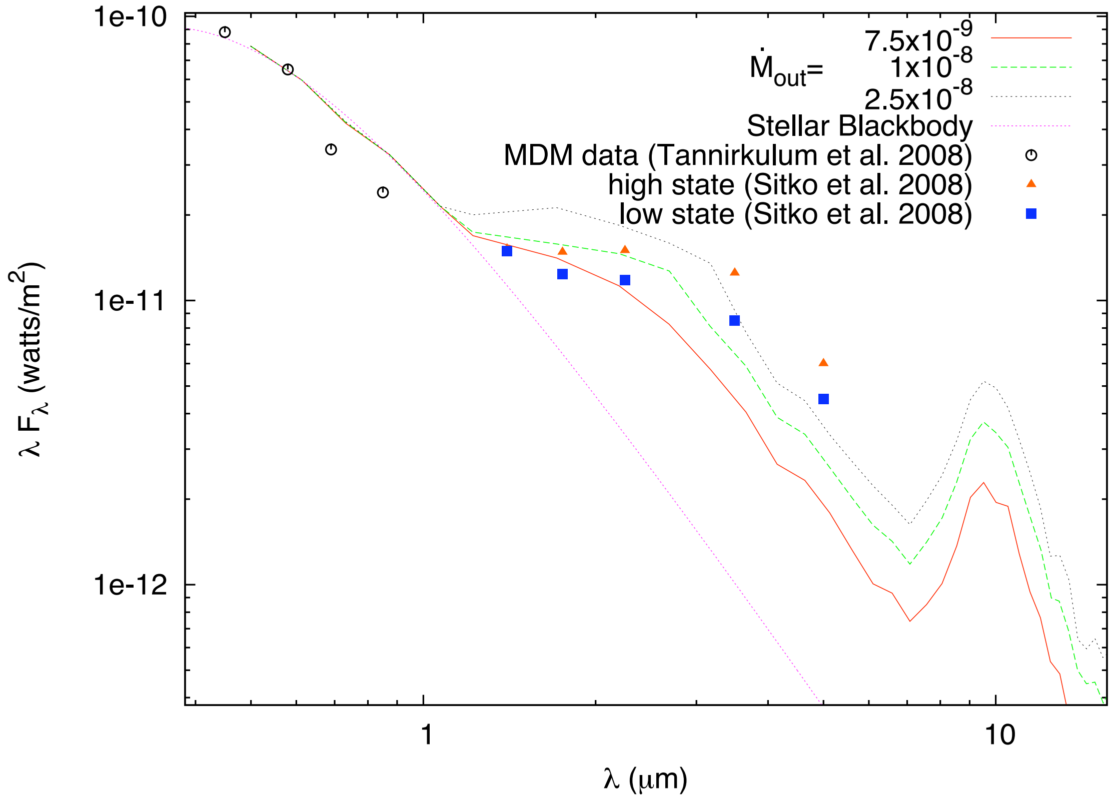


neutral gas
+ dust
ionized gas
dust sublimation surface
Accretion
Disk
UV & X-ray
continuum
low
partial
ionization
high
IR emission
X-ray absorption
Broad-Line Region

- The large volume of dusty gas in the wind beyond the dust sublimation region reprocesses the central continuum radiation to infrared wavelengths and naturally accounts (together with the disk) for the near-IR excess (the "$3\,\mu$m bump") in Seyfert galaxies and QSOs. The apparent reduction in the height of the "obscuring torus" in luminous AGNs is readily attributed in this scenario to the effect of radiation pressure on dust.

- The same model can successfully account for the near-IR excess, the extended nature of the NIR emission region (as inferred from interferometry), and the hot gas emission within the dust sublimation radius in Herbig Ae YSOs, as well as for the apparent flattening of the reprocessing surface in the higher-luminosity Herbig Be stars (Bans & Königl 2011).

Disk-wind model fits to the NIR excess of the Herbig Ae star MWC 275



N.B. Other proposed models cannot account for the high state.

Correlations between Accretion and Outflow Diagnostics

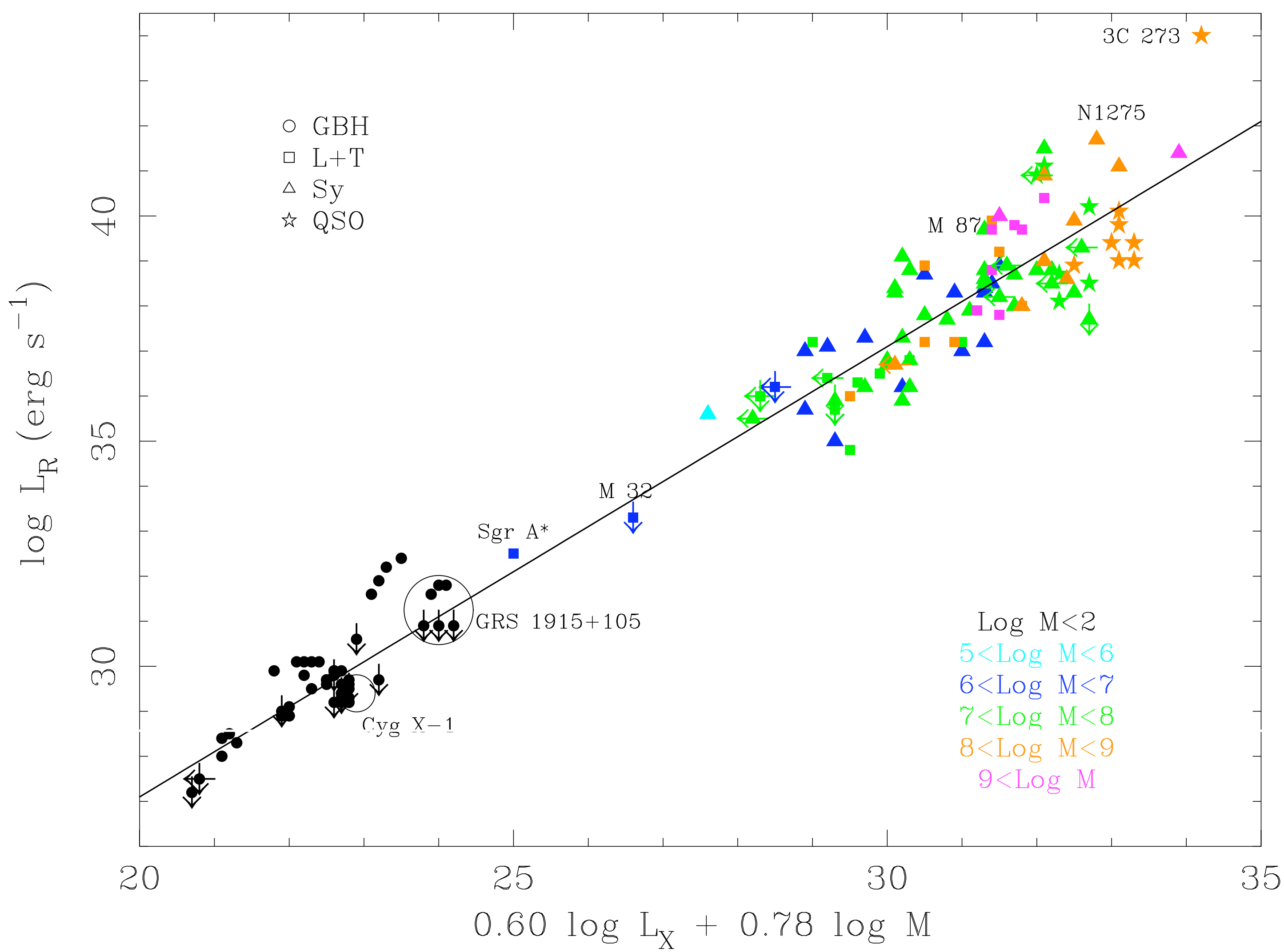
A scaling relation between the radio ($L_{\rm R}$) and X-ray ($L_{\rm X}$) luminosities, normalized by the BH mass M, was found to apply to both Galactic BH sources and AGNs (Merloni, Heinz, & Di Matteo 2003; Falcke, Körding, & Markoff 2004):

$$\log L_{\rm R} \approx 0.60 \log L_{\rm X} + 0.78 \log M + 7.33$$

- The power-law exponent $q = 0.60$ in the relation $L_{\rm R} \propto L_{\rm X}^q$ has a $1\,\sigma$ error range of ± 0.11.

- Galactic BHs exhibit this correlation in the low/hard state, during which a steady radio jet is produced. For this subset of objects, the power-law exponent is steeper ($q \approx 0.7$).

Fundamental Plane of Accreting BHs (Merloni et al. 2003)



♣ The observed diagnostics have received different physical interpretations.

- The radio luminosity has been related to the jet kinetic luminosity $L_{\rm jet}$ by $L_{\rm R} \propto L_{\rm jet}^{\frac{17}{12}-\frac{2}{3}\alpha_{\rm R}}$, assuming optically thick synchrotron emission with spectral index $\alpha_{\rm R}$ (e.g., Markoff et al. 2003).

- The X-ray emission was interpreted as optically thin synchrotron emission from the jet (Markoff, Falcke, & Fender 2001; Giannios, Kylafis, & Psaltis 2004).

- Alternatively, the X-ray emission was interpreted as thermal radiation from the disk (e.g., Fender, Gallo, & Jonker 2003; Körding, Fender, & Migliari 2006), which, in the low/hard state, is radiatively inefficient. In this picture, $L_{\rm jet} \propto \dot{M}_{\rm in}$ (the mass accretion rate) in the hard state.

! Some of the AGNs that follow the fundamental plane evidently do not correspond to the hard state.

A Fundamental Plane of Accreting YSOs(?)

- Correlations between accretion and outflow diagnostics that are similar in form to the fundamental plane for accreting BHs have been found also in YSOs and span the full range of protostellar masses.

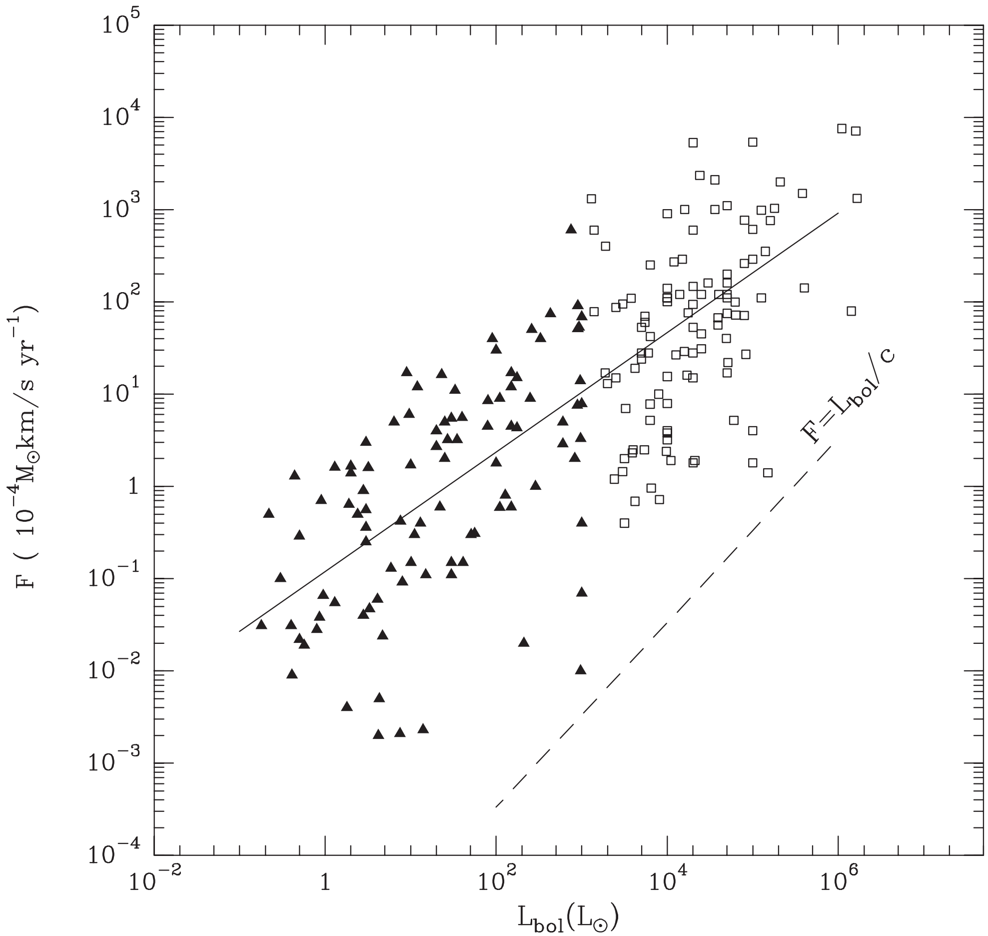
♣ In contrast to the situation in XRBs and AGNs, in the case of YSOs the measured quantities provide direct information about the accretion and outflow processes.

- In particular, from measurements of the outflow speeds, spatial scales, and mass content of the bipolar lobes, one can measure $\dot{M}_{\rm lobe} V_{\rm lobe}$, which, by momentum conservation, is equal to $F \equiv \dot{M}_{\rm jet} V_{\rm jet}$.

Independent measurements of $V_{\rm jet}$, which varies over a narrower range, can be used to infer also the behavior of $\dot{M}_{\rm jet}$ and of $L_{\rm jet} \propto \dot{M}_{\rm jet} V_{\rm jet}^2$.

- Another measured quantity is the bolometric luminosity $L_{\rm bol}$, which, after subtracting the intrinsic stellar luminosity, yields the accretion luminosity $\propto \dot{M}_{\rm in}$.

  - YSO jets also emit (in this case thermally) in the radio, and $L_{\rm R}$ is found to be well-correlated with $L_{\rm bol}$, at least up to $10^4\ L_\odot$ (Cabrit & Bertout 1992). Note, however, again that for these sources $L_{\rm R}$ is *not* the primary diagnostic of the jet kinetic luminosity.



Wu et al. (2004)

Least-squares linear fit: $\log F = (0.648 \pm 0.043) \log L_{\rm bol} + const$

- Earlier compilations have yielded similar results:

$$\dot{M}_{\rm jet}\dot{V}_{\rm jet} \propto L_{\rm bol}^{p}\,,\, p \sim 0.6 - 0.7$$

(e.g., Lada 1985; Levreault 1988; Cabrit & Bertout 1992; Edwards, Ray, & Mundt 1993; Shepherd & Churchwell 1996; Henning & Launhardt 1998; Beuther et al. 2002).

The power-law index p is inferred to be larger in the lowest-luminosity ($L_{\rm bol} \lesssim 10\, L_{\odot}$) sources (e.g., Bontemps et al. 1996).

Physical origin of observed $F - L_{\rm bol}$ correlation in YSOs(?)

• Focus on the dependence of $\dot{M}_{\rm jet}$ (which dominates the behavior of F) on $\dot{M}_{\rm in}$ in high-luminosity sources.

• The highest momentum discharge will arise from the vicinity of the YSO, on a spatial scale $\sim R_*$ that does not vary strongly from source to source. Estimate: $\dot{M}_{\rm jet} \propto \rho_{\rm disk}\sqrt{T_{\rm eff}}$. (Other, somewhat different, prescriptions are also plausible.)

• Adopt a generic Shakura & Sunyaev (1973) disk model, which was previously applied to the study of accretion disks around massive protostars by Vaidya, Fendt, & Beuther (2009).

Find: $\dot{M}_{\rm jet} \propto \dot{M}_{\rm in}{}^{r}$, with $r = 0.59$ in region b (Thomson opacity) and $r = 0.68$ in region c (Kramers opacity).

Conclusions

- Although YSO outflows are not relativistic, they represent an observationally accessible example of the ubiquity of jets in accreting astronomical objects and provide an illuminating context for the study of relativistic sources.

- Among the common issues that are encountered in the study of YSO and XRB/AGN outflows is the relative contribution of the accretion disk and the central source, and the origin of the magnetic field implicated in driving the jets.
  - Disk outflows that do not originate in the immediate vicinity of the central source could play a critical role in the confinement and collimation of highly relativistic jets.

- Dusty disk outflows may have similar spectral imprints in both AGNs and YSOs.
  - The outer portions of AGN winds may be launched from molecular disk regions that are similar in certain respects to protostellar disks.
- The measured correlations between accretion and outflow diagnostics in YSOs might shed light on the nature of the fundamental plane of accreting BHs.