Disk-Star-Wind Interactions

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Outline:

(1) Introduction

i) Relevant observations of protostellar disks and outflows and of the disk-wind connection.

ii) Evidence for magnetic star-disk interactions.

iii) Physical mechanisms for driving bipolar outflows and jets from protostellar systems: the role of magnetic, thermal, and radiation-pressure forces; effect of large-scale magnetic fields; interstellar vs. stellar magnetic fields; steady vs. episodic ejection.

$(2) - (3)$ Structure of Magnetic Wind-Driving Disks

i) Vertical angular momentum transport by large-scale magnetic fields – magnetic braking and centrifugally driven outflows.

ii) Magnetic diffusivity in the ambipolar, Hall, and Ohmic conductivity regimes.

iii) Exact MHD disk/wind models and their physical interpretation; the incorporation of both vertical and radial magnetic angular momentum transport.

iv) Global solutions; strongly coupled vs. weakly coupled disk configurations.

v) Stability considerations.

4) Disk Formation Mechanisms

i) Gravitational collapse of molecular cloud cores.

ii) Magnetic field advection and angular momentum transport.

iii) Exact numerical and semianalytic solutions and their astrophysical implications.

iv) Initiation of outflows.

(5) Disk–Star Magnetic Coupling

i) Conceptual framework — semianalytic models and numerical simulations.

ii) Implications to stellar rotation periods and to nonsteady outflows.

iii) Field-line opening and other open questions.

- Recapitulation

The Disk–Wind Connection

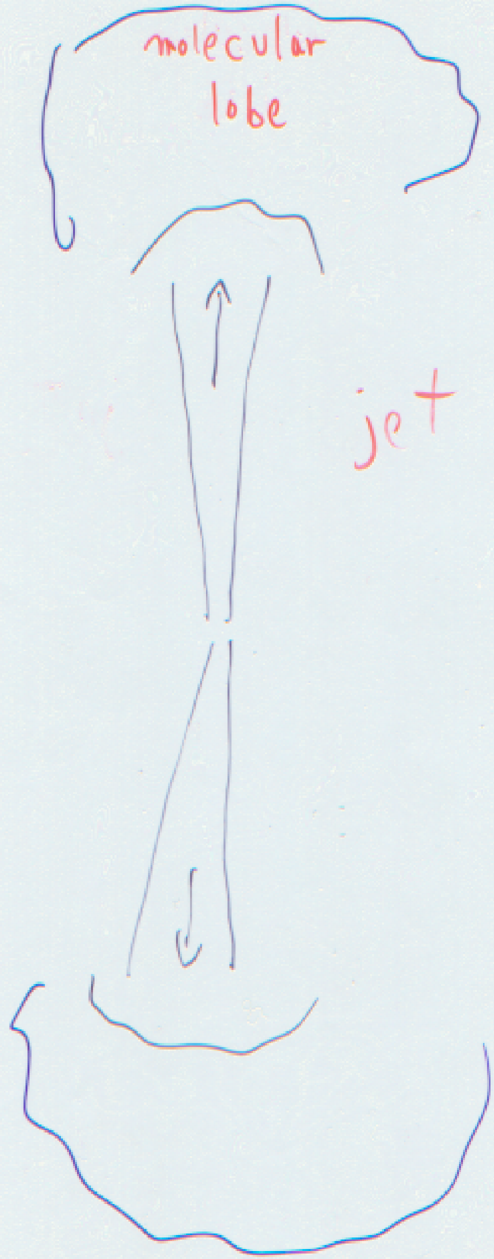
Bipolar outflows and jets

- Bipolar molecular outflows and narrow atomic (but sometimes also molecular) jets are ubiquitous phenomena in protostars (nearly 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 ($L_{\rm bol} < 10^3 L_\odot$) young stellar objects (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 $10^3 - 10^4$ AU.

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

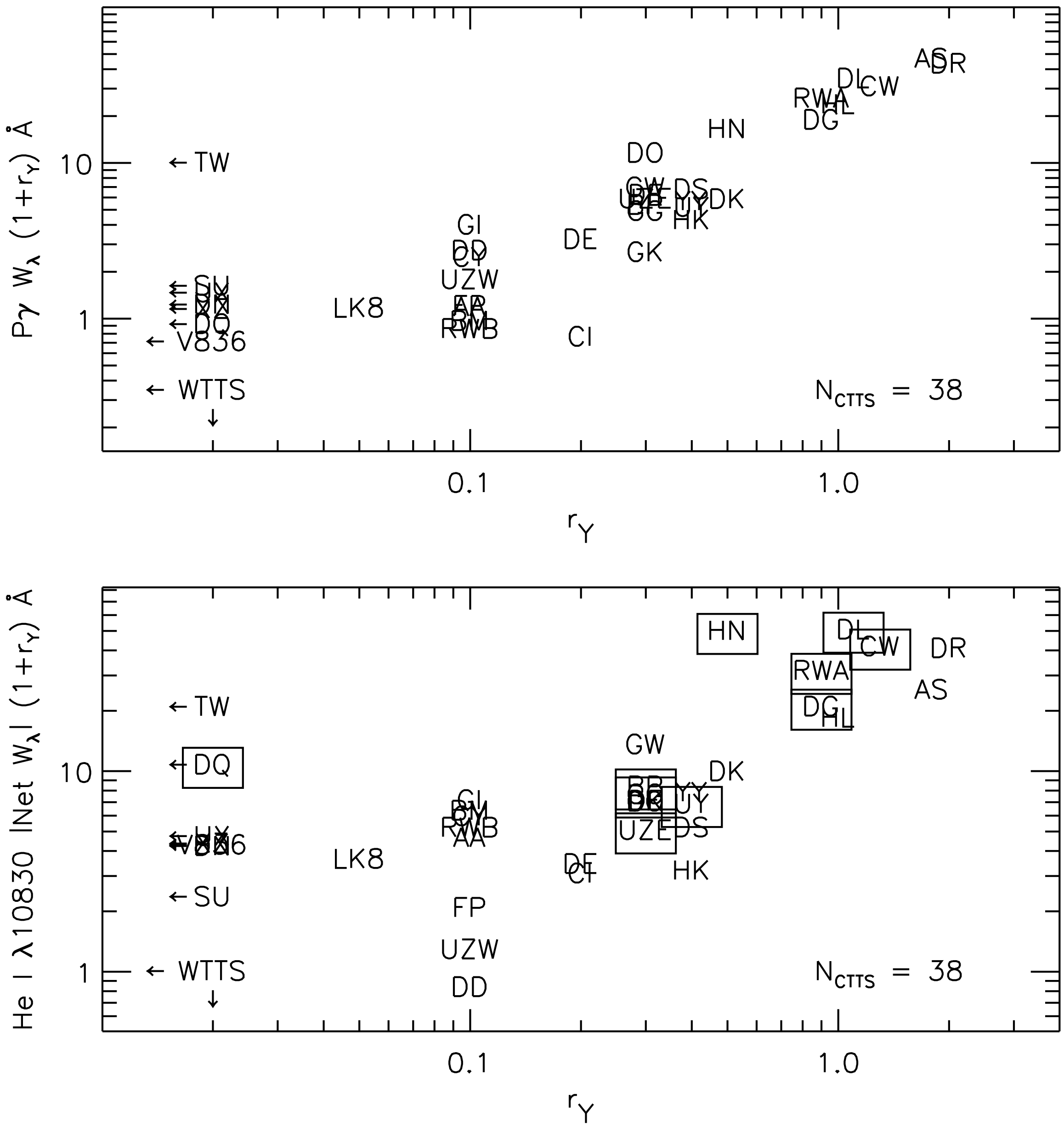

molecular
lobe
jet

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. The most recent results (Podio et al. 2006) yield an average mass outflow rate of $5 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, markedly higher than previous estimates.

A significant number of outflows have also been detected by optical observations of intermediate-mass ($2 \lesssim M_*/M_\odot \lesssim 10$) 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_{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.



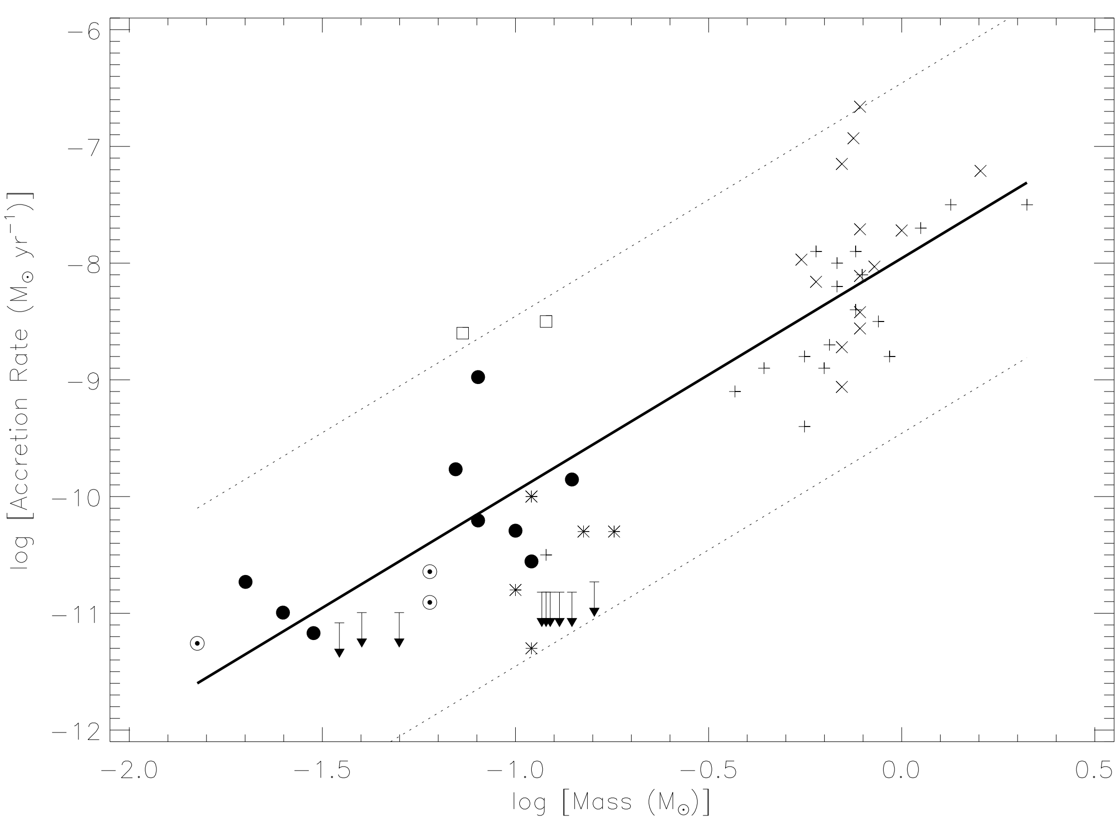
NIRSPEC/Keck II — Edwards et al. (2006)

- 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 $\sim 10\ M_{\odot}$.

- Correlations of the type $\dot{M} \propto L_{\rm bol}^q$ ($q \sim 0.6 - 0.7$) were found in both low-M_* and high-M_* YSOs for mass accretion rates and for mass outflow rates in ionized jets as well in bipolar molecular lobes. Typically, $\dot{M}_{\rm out}/\dot{M}_{\rm in}$ is inferred to be ~ 0.1 (e.g., Kurosawa et al. 2006).

- CTTs-like accretion and outflow phenomena have now been found also in very-low-mass stars and brown dwarfs; the relation $\dot{M}_{\rm in} \propto M_*^2$ appears to apply (with considerable scatter) over more than 2 orders of magnitude in M_* (Mohanty et al. 2005).



♣ 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 high- (or at least intermediate) 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 $M_* \sim 20\ M_\odot$.

- Strong evidence for a disk origin of outflows is available for FU Orionis outbursts in rapidly accreting young YSOs. It is inferred that the emission during an outburst (of typical duration $\sim 10^2$ yr) originates in a rotating disk and that the outflow represents a wind that accelerates from the disk surface (with $\dot{M}_{\rm w}/\dot{M}_{\rm in} \sim 0.1$; $\dot{M}_{\rm in} \sim 10^{-4}\ M_\odot\ {\rm yr}^{-1}$). It has been suggested (Hartmann 1997) that most of the mass accumulation and ejection of YSOs occurs during recurrent outbursts of this type.

Magnetic fields in outflow sources

A long-established (albeit still debated) scenario for the origin of low/intermeidate-M_* YSO/disk systems is that they are produced in the collapse of rotating molecular-cloud cores originally supported against gravity by large-scale magnetic fields (and hydromagnetic waves). The collapse is triggered by ambipolar diffusion (the relative drift between ions and neutrals) that brings the inner core mass above the critical value for collapse. The rotation axis of the YSO/disk is by and large expected to be parallel to $\mathbf{B}$.

- This picture is supported by FIR and sub-mm polarization measurements, which reveal an ordered, hourglass-shaped field morphology on sub-pc scales.

- Further support comes from H I and OH Zeeman measurements of the line-of-sight field amplitude, and estimates of the plane-of-sky field strength using the measured dispersion in the field orientation (Chandrasekhar-Fermi method), both of which typically imply roughly virialized cores.

- When both the inner-disk polarization and that of the foreground cloud can be measured simultaneously, one typically infers that the rotation axis is aligned with the direction of the large-scale magnetic field (e.g., Vink et al. 2005).

* The projected orientations of CTT disks do not, however, appear to be correlated with the direction of the local field (Ménard & Duchêne 2004). One possible explanation is that the field was initially comparatively weak and misaligned with the core rotation axis (Matsumoto et al. 2006).

Direct measurements of $\mathbf{B}$ in either the outflow or the disk have been rare.

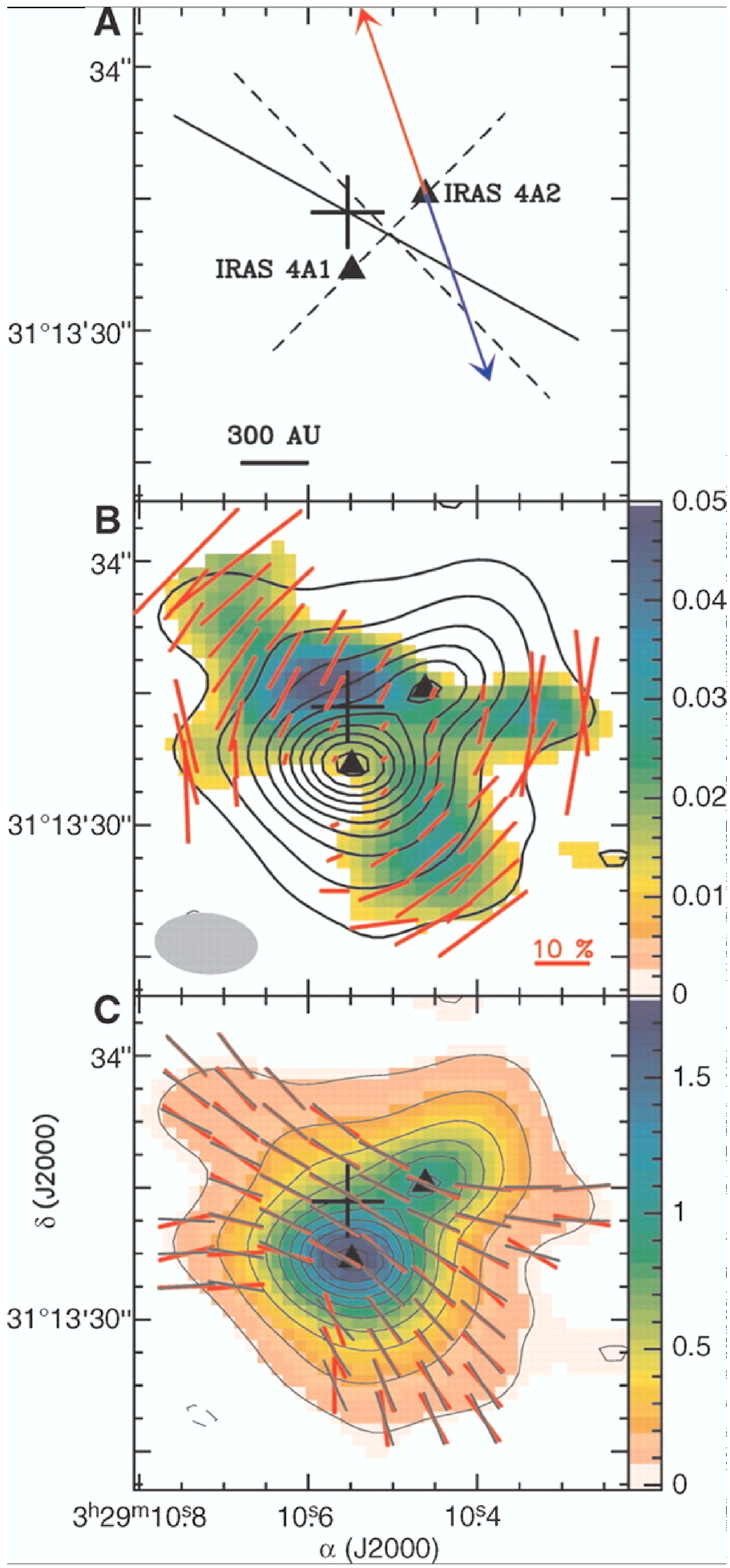
- Strong circular polarization detected on scales of $20\ \mathrm{AU}$ in T Tau S (Ray et al. 1997) was interpreted as field of at least several gauss advected from the origin by the associated outflow.

- Meteoritic evidence points to the presence in the protosolar nebula of a $\sim 1\ \mathrm{G}$ field at $r \sim 3\ \mathrm{AU}$.

- A Zeeman-signature least-square deconvolution measurement in FU Ori (Donati et al. 2006) was interpreted as a $\sim 1\ \mathrm{kG}$ field (with $|B_\phi| \sim B_z/2$) originating on scales of $\sim 0.05\ \mathrm{AU}$ in the associated disk (with Ω_K and B_ϕ having opposite senses).

Further support for a magnetic disk–outflow connection has been inferred from measurements of apparent rotations in the jets (lecture 2).

$\vec{\Omega}$
$\vec{B}$

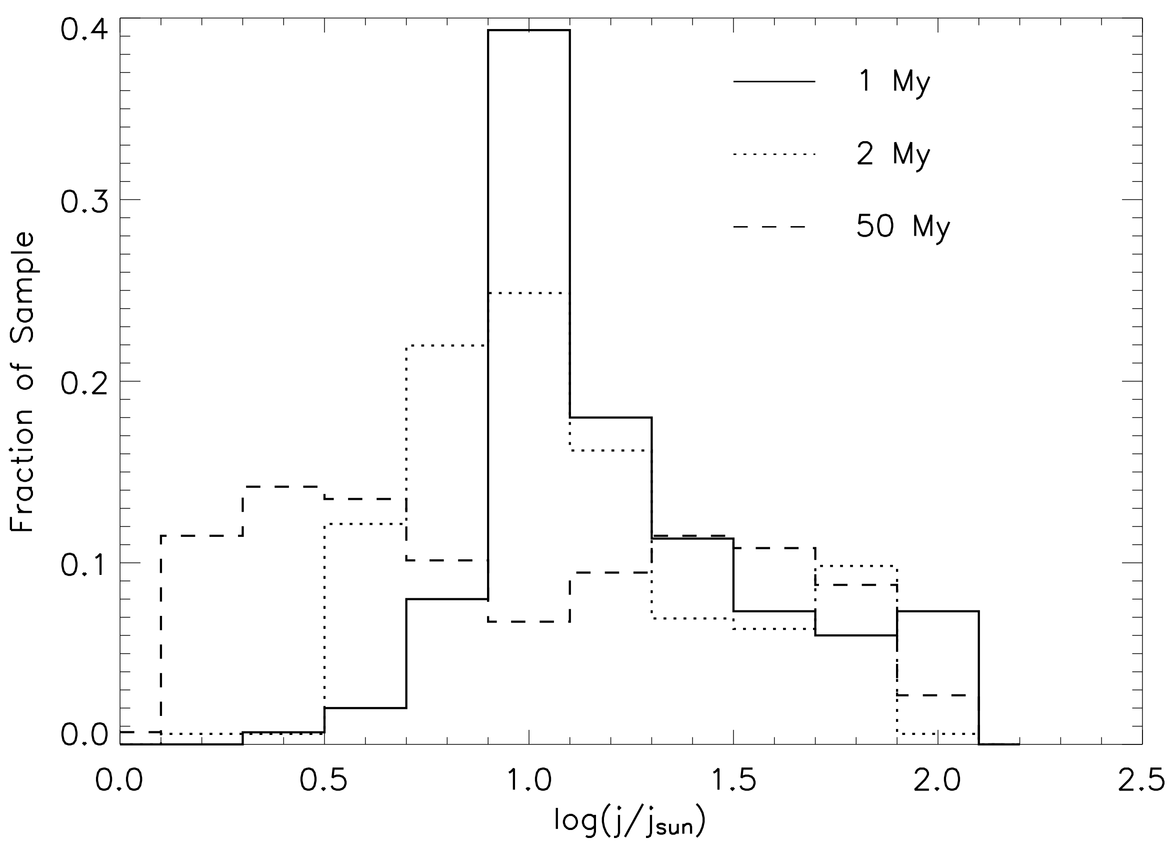


$877\,\mu$m SMA observations of NGC 1333 IRAS 4A
(Girart et al. 2006)

Star-Disk Interactions

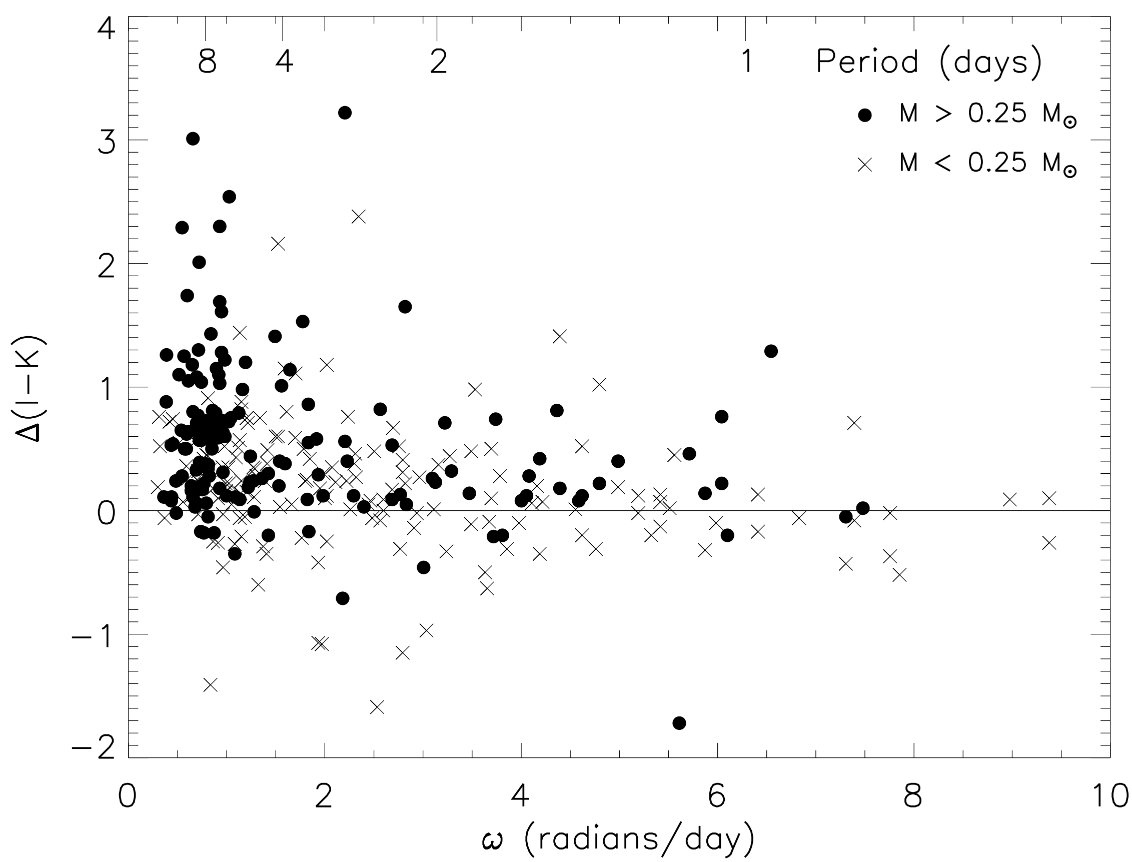
Stellar rotations and accretion

- It is now well established (based on ~ 1700 measured rotation periods) that about 50% of sun-like YSOs ($M_* \sim 0.4 - 1.2\ M_\odot$) undergo significant rotational braking during their PMS contraction to the ZAMS, and that the ones whose specific angular momenta decrease with time are essentially the ones that are already slowly rotating at an early age (~ 1 My).

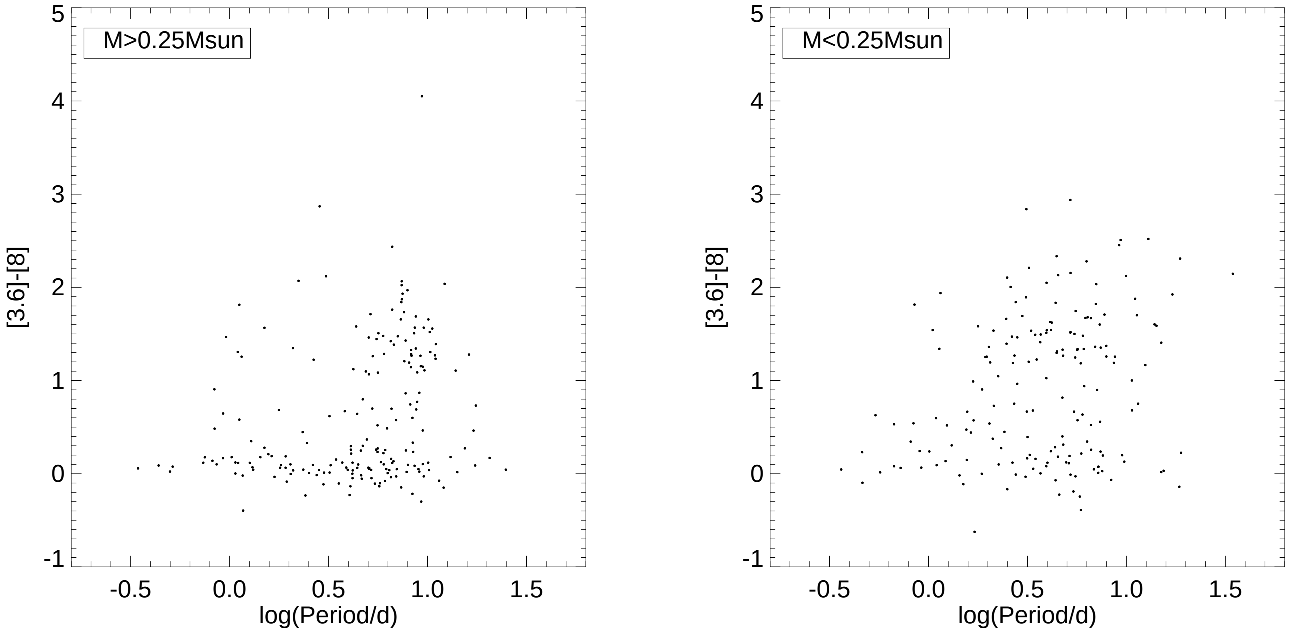


Herbst & Mundt (2005)

- There is a clear correlation between having a comparatively long period ($\gtrsim 2\mathrm{d}$) and exhibiting an accretion-disk signature (NIR or MIR excess). This trend is particularly noticeable in higher-mass ($\gtrsim 0.25\ M_{\odot}$) YSOs, but it is also found in very-low-mass stars and brown dwarfs (in which, however, the braking efficiency is evidently lower).



Near-IR MPG/ESO $2.2\,\mathrm{m}$ data (Herbst et al. 2002)



Mid-IR *Spitzer* data (Rebull et al. 2006)

- The connection with disks is supported by the fact that the inferred maximum stellar braking times ($\sim 5-10$ Myr) are comparable to the maximum apparent lifetimes of gaseous accretion disks (~ 1 Myr for $\sim 50\%$, ~ 5 Myr for almost all stars).

♣ These results imply that the dominant braking mechanism in YSOs is directly tied to active disk accretion. In the absence of such accretion (or after the disks disperse), PMS stars nearly conserve specific angular momentum and therefore spin up as they contract to the ZAMS. Stellar magentic fields likely play a key role in the braking process (lecture 5).

Disk truncation and field-channeled accretion

As was originally inferred in the case of accreting magnetized neutron stars and white dwarfs, a sufficiently strong stellar magnetic field can truncate the accretion flow, with the truncation radius increasing with B and decreasing with $\dot{M}_{\rm in}$. The intercepted accreting matter can be expected to "climb" onto the field lines and be magnetically channeled to some finite stellar latitude. By the time the matter reaches the stellar surface it is streaming along the field lines with near free-fall speeds and is therefore stopped in an accretion shock.

The basic elements of this scenario are supported by observations of CTTs (as well as Herbig Ae/Be stars, which so far have been less well-studied):

- Common occurrence of inverse P Cygni profiles with reshifted absorption reaching several hundred $\mathrm{km\,s^{-1}}$.

- Observed hydrogen and Na I line profiles can be adequately modeled in this picture; predicted statistical correlations between line fluxes and $\dot{M}_{\rm in}$ have been found in the UV–NIR spectral range.

- Observed spectral energy distributions of optical and UV excesses are successfully reproduced by accretion shock models.

- Periodic visual-flux variations due to "hot spots" (interpreted as nonaxisymmetric accretion shocks on the stellar surface) are only observed in actively accreting CTTs (but *not* in WTTs). However, in contrast to "cool spots" (the analogs of sunspots), which last for $\sim 10^2 - 10^3$ rotations, the hot-spot periodicity only persists for a few rotation periods, indicating a highly nonsteady configuration. This inference is supported by the detection of high-amplitude irregular flux variations.

- Strong NIR veiling variability can be interpreted in the context of this picture as arising in the interaction region between the disk and an inclined stellar magnetosphere, with possible contributions also from the accretion shock and from the shock-irradiated zone in the inner disk.

- Zeeman-broadening measurements in a growing number of CTTs have yielded an intensity-averaged mean surface magnetic field strength of ~ 2.5 kG, with the field inferred to reach $\sim 4-6$ kG in some regions. This is consistent with the model predictions.

- Circular polarization measurements in lines associated predominantly with the accretion shock have demonstrated that the field is highly organized (with peak value ~ 2.5 kG) in the shock region (covering $< 5\%$ of the stellar surface); this polarization is rotationally modulated.

  There is, however, no net polarization in photospheric absorption lines, implying a complicated surface field topology (with a global dipole component $\lesssim 0.1$ kG).

Magnetospheric accretion models further predict that nonsteady outflows could be produced in the course of the star–disk interaction. There is now observational evidence for accretion-induced winds in CTTs emanating from both the inner disk and the star. The stellar component has been inferred to move radially out and to undergo full acceleration (to $\sim 400\ \mathrm{km\,s^{-1}}$) in the stellar vicinity (Edwards et al. 2006).

Outflow Mechanisms

Driving forces

- The momentum discharges inferred from observations of protostellar jets are compatible with the values deduced for the bipolar molecular outflows but are typically a factor $\sim 10^2$ higher than the radiation-pressure thrust $L_{\rm bol}/c$, ruling out radiatiative acceleration as a dominant driving mechanism in low/intermediate-M_* YSOs.

  Radiative effects could however be important in driving photoevaporative disk outflows, particularly in high-$L_{\rm bol}$ systems (e.g., Hollenbach et al. 1994). Disk heating by a luminous YSO (such as a Herbig Be star) could potentially also induce a line-driven wind from the inner-disk surface (Drew et al. 1998). Another effect is radiation pressure on the dusty outer regions of a disk wind even in comparatively low-$L_{\rm bol}$ systems (lecture 2).

- Thermal pressure acceleration has been discounted as a dominant mechanism since the requisite high ($\sim$ virial) temperatures are not generally observed at the base of the flow.

  It has nevertheless been suggested that, under suitable conditions, the thermal energy released in shocks at the boundary layer between the disk and the star could be efficiently converted into outflow kinetic energy (Torbett 1984; Soker & Regev 2003).

  Even if this is not a dominant mechanism, thermal pressure could potentially still play a significant role in driving hydromagnetic disk winds (e.g., Pesenti et al. 2004; lecture 2).

- A general result for YSO jets can be obtained by combining

  1. $\dot{M}_{\rm jet} V_{\rm jet} \sim 10^2 \ L_{\rm bol}/c$
  2. $L_{\rm jet} \sim \dot{M}_{\rm jet} V_{\rm jet}^2$
  3. $V_{\rm jet} \sim 10^{-3} \ c$
  4. $L_{\rm bol} \sim L_{\rm acc} \ (\sim GM_* \dot{M}_{\rm in}/R_*)$,

  which implies that, on average, $L_{\rm jet} \sim 0.1 \ L_{\rm acc}$. Such a high ejection efficiency is most naturally understood if the jets are driven hydromagnetically.

Origin of magnetic field

- A natural origin for a large-scale, open magnetic field that threads the disk and can drive a "centrifugal" outflow is the interstellar field that supports the natal molecular-cloud core.

  If angular momentum transport in the disk is associated with a turbulent viscosity that is of the same order as the magnetic diffusivity, then the field lines will stay put and will not be advected by the accretion flow from large to small radial scales (Lubow et al. 1994a). However, if this is not the case (e.g., the angular momentum transport is dominated by a disk outflow, or the transport coefficients are anisotropic), then the field could be advected inward (lecture 4).

- An alternative possibility is that the outflow is driven by the stellar field (by field lines attached to the stellar surface or by effectivly severed lines that have penetrated the disk). This option is relevant to models of outflows that originate in the disk/stellar-magnetosphere interaction (lecture 5).

- It has also been proposed that a large-scale, open field could be generated by a disk dynamo (e.g., Tout & Pringle 1996; von Rekowski et al. 2003; Blackman & Tan 2004).