Jets and Outflows: From Star to Cloud


Where do we see jets?

Class 0 Protostars

HH 212 McCaughran et al

0.15pc = 30,000 AU

Evolved Class 1 Protostars

HH111 Reipurth & Bally

10,000 AU

Class 2  Disk only

Universal across evolutionary stages
Accretion-powered Mjet/Macc ≈ 0.1
(Edwards+2006, Antoniucci+2008)

Universal in $M^*$: from 24 Mjup to 10 M
Vjet ≈ 100-800 km/s

HH 30 Stapelfeldt et al 1999

1000 AU
Why Do Jets Matter?

- Invoked to solve several major issues in SF:
  - Low SFE and SFR in turbulent clouds
    - Cf. chapters by Padoan, Krumholz...
  - 30% Core to Star efficiency
    - cf. chapters by Offner, Padoan...
  - Removal of star/disk angular momentum
    - cf. chapters by Li, Bouvier, Turner

- Also:
  - May affect planet formation and photoevaporation
    - cf. chapters by Dutrey, Pontoppidan, Alexander, Gail...
  - Unique info on source binarity, variability, axis precession
    - cf. chapters by Reipurth, Audard...
Remarkable progress since PPV

- First observational access to
  - New spatial ranges <50 AU to >10pc
  - New λ ranges (Xrays, IR, submm)
  - Detailed proper motions over > 10 yr

- Large-scale collaboration networks
  - JETSET (2005-2008) EU (11 institutes)
  - JETPAC (2008-current) USA-UK (5 institutes)

  Combining observations, MHD simulations & theory, and high-energy density lab experiments (HEDLA)
Once the initial conditions are normalized, the problem depends on the rotation rate. In Section 2.2, this corresponds to a stellar magnetic field with a Keplerian corotation radius (2002) and Matt & Pudritz (2005a), the disk magnetic resistivity, this periodicity has to be considered carefully.

Using case C03 as a representative example, we are going to analyze the dynamical properties of interacting star-disk systems characterized by different resistivity coefficients \( \alpha \) and \( \delta \), so that the magnetic configuration opens up closer to the star: since the opening of the magnetosphere is determined by different dynamical processes associated with the inflation and opening of the magnetosphere close to the star. Three classes of outflows correspond to the other Stellar Wind.

Jet angular momentum and launch process.

Zanni & Ferreira 2013, A&A
Jet Collimation

- Same width and collimation scale in class 0 as class 2 jets! (Cabrit et al 2007)
  - Not hydro collimation by envelope
- Need disk B field for jet collimation!
  - MHD disk wind is most efficient collimator.

HH212 jet at PdBI 0.3” across jet
Codella et al 2007

Meliani et al 2006, A&A
Jet rotation

Observed Radial Velocity Shift

Class 2: DG Tau with HST (Bacciotti+2002, Coffey+2007)

Class 1: CB 26 in CO with PdBI (Launhardt et al 2009)

Stationary MHD disk winds predict (Anderson+03. Ferreira+06)

\[ 2rV_\phi\Omega_0 = V_p^2 + 3\Omega_0^2r_0^2 \]

\[ \Rightarrow \text{suggests } r_0 \approx 0.1 - 5 \text{ AU for all candidates so far} \]

Feedback on disk structure in the region of formation of terrestrial planets
Questioning Jet Rotation

- Puzzling observations (RW Aur, HH212…)
  - Opposite rotation sense of Disk / Jet or Jet / Counterjet
  - Variability in a few years
    (Cabrit et al 2006, Codella et al 2007)
    (Coffey et al 2012, Davis et al 2001)

- Proposed interpretations
  - Shocks in MHD disk wind (Fendt 2011, Sauty 12)
  - Beam dilution of jet rotation signatures?
    (Pesenti et al 2004)

To be continued …
Resolving Central Engine in Br\(\gamma\)

- Interferometric sizes
  - 0.1 AU < R(Br\(\gamma\)) < 2\(\mu\)m continuum

- Spectrally resolved interferometry
  - Bipolar jet in outbursting Herbig Be

- Fitting of flux, visibility, and phase in Herbig Be MWC297
  - rotating MHD disk wind favored over polar stellar wind
  - Launch zone 0.5 – 1 AU
  See also Malbet+2007; Rousselet-Perraut+2010 for H\(\alpha\) in AB Aur

![Graph](image_url)
X-Ray Jets

- From 30 AU to pc scales
  - \( T_X \) implies \( V_s \sim 500 \text{ km/s} \)
  - \( \gg \) optical lines
  - Tenuous fast stellar wind?

- Innermost structures seem stationary
  - Collimation shock?
  - Magnetic heating? (See poster by Schneider et al.)
  - Impact on disk irradiation

DG Tau
30 AU
Güdel+ in prep

DG Tau
1200 AU
Güdel+ 2008
A&A,478,797

HH 80
2.5 pc
Pravdo+ 2004
ApJ, 605, 259
Magnetic Tower (HEDLA)

- Magnetic Driven Cavity
- Axial Jet: hoop stress
- Cavity confined by ambient medium
- Kink unstable: fast collimated clumps

**Impact on Planet Formation**

- **Disk irradiation**
  - X-rays/UV from collimation shock
  - Shielding by (dusty) disk wind

- **MHD disk winds from 0.1-10 AU**
  - Radial transport at sonic speed
  - Lifting and melting of solids
  - Planet migration? (e.g. Terquem 2006)

Panoglou et al 2012, A&A
Intermediate scales 100 AU – 1 pc

Jet structure, propagation and variability

Visser et al 2012, A&A
Core to star efficiency

- 3D MHD collapse simulations
  - $M_{\text{star}} \approx 50\% \ M_{\text{tot}}$ for $B$-$\Omega$ angle up to 50°
  - Protostellar MHD ejections determine final stellar mass?
  - Outflow base broadens in time
    - See also Offner+2011

Ciardi & Hennebelle 2010, MNRAS
Machida & Hosokawa (2013)
Outflow-Envelope Interactions: widening of outflow cavity with time

Class 0

Cavity o.a. ~ 20-50°. Outflow starts entraining dense envelope

Class I

Cavity o.a. ~ 80-120°.

early Class II

Very wide cavity o.a. > 100-130°. Low-density (or no) envelope left

late Class II

Quasi-spherical shell. Not clear how common this is.
Wide-angle component(s)

- Invoked for CO cavity expansion (cf. Arce et al 2007, PPV)
- Must be slower than jet
  - Highly curved bowshocks
  - Velocity decrease at jet edges (Bacciotti+2000, Coffey+2008, Agra-Amboage +2011)
  - Not a « classical » X-wind
- Possible origins
  - Slower disk wind ?
  - Outflow from 1st core phase ?
Multiple jet components

- **Spitzer & Herchel:** Jets often have both atomic & molecular components
- with range of V and T
  - Shocks
  - range of launch radii?
- Need to revisit mass fluxes
  - Outflow power vs Lacc!

Chemical diagnostics of $R_{\text{launch}}$

- $R_{\text{launch}} > R_{\text{sub}} \text{ Fe, Si, Ca}$
  depletion at small $z, V$
  

- Chemical models of dusty MHD disk winds
  (Panoglou et al 2012)
  - Molecules can survive!
  - Reproduce Herschel H$_2$O broad component in Class 0

- Next step: CO with ALMA, H$_2$ with AO

Models: Yvart et al. 2013
Data: Kristensen et al. 2012
Jet variability record

- **Knots & Bows = internal shocks**
  - Velocity and/or angle variations. **not pure** Mdot var

- **Angle variations:**
  - S-shaped precession 3000-50,000 yrs
  - **Orbital motion:** HH211, P=43 yrs; HH111, P=1800 yrs Lee+2010, Noriega-Crespo+2011
    - constrain binary mass and separation
Velocity Variability

- 3 preferred time scales
  ≈3-10 yrs, ≈100 yrs, ≈1000 yrs
  ΔV of 20-140 km/s


- May probe
  - Stellar magnetic cycles
  - perturbations by companion
  - link with EX Or / FU Or outbursts? (cf. Audard et al. Chapter)
HH1: Clumps & Cloud Entrainment
HH37: Clumps & Mach Stems

Red: [S II]  
Green: H-alpha

1994.8

1000 AU
MHD Jet Synthetic Observations

- Non-equilibrium ionization
- AMR resolves cooling zone
- Hα & [SII] maps (Hansen et al. 2013)
HEDLA Studies: Mach Stems

- Bright HH34 bright spots (Hartigan et al 14)
  - Clumps?
  - Shock intersections (Mach stems)?

![Diagram of Mach Stems and shock intersections](image.png)
Cluster/Cloud Scales > 1 pc

Outflow feedback

Overlapping Outflows In Serpens
Graves et al 2010
Outflow Feedback

- Simulations: Outflow feedback needed?
  - Sustain turbulence
  - Reduce SFE
  - Reduce stellar masses

- Focus on processes observational connections

(see also: Li et al. 10, Krumholtz et al. 12)
Giant Outflows

- 0.1 Myr at 100 km/s = 10 pc
- How much jet momentum stays in cluster? In cloud?

Example: B5 – IRS1 Molecular Outflow

CO (1-0) map from Arce et al. (2010)
Importance of Fossil Cavities

- Momentum rate balance is what counts
- Perseus: Outflow momentum rate 40% – 80% turbulence diss. rate
- Large contribution in low V fossil shells
  - Quillen (05), Arce (10,11)

(see also: Nakamura et al 11, Aspen 03, Graves et al 10)
Outflows/Cloud Coupling

- Prompt Entrainment (Shocks)
  - Jet precession/ Binary/ wandering; periodicity/ clumpiness

- Randomize bulk flow
  1. Interaction with existing turbulent flow
  2. Interaction of multiple fossil shells.

Precession + Pulsing: Raga et al 09

Outflows Re-energize Turbulence
Cunningham et al 09
Outflow Driven Turbulence

- Interaction of multiple fossil shells different from “Fourier” driving
  - Knee in spectra
  - Steeper power spectrum

\[ E(k) \propto k^{-3} \]

Carroll et al 09, 10
Nakamura & Li 07, 11

Energy spectra from 3 feedback simulations (Carrol et al 2010)
Observation vs. Theory

- No evidence for small scale injection?
  - Principle Component Analysis
    - Brunt et al. 09
  - Power Spectra (VCS method):
    - Padoan et al. 09
- PCA: Can’t pick up outflow driving scale!!! (Carrol et al 2010)
- VCS Power Spectrum
  - Optical depth (?)
  - Multiple Interaction scales (?) (Arce 2010)
Feedback: Cloud scales (!)

Orion BN/KL outburst
- $E \sim 10^{47}$ erg
- Triple star dynamical interaction
  - (Bally et al 2011)
Conclusions

- Jets and outflows not only beautiful and dynamic; fundamental to understand star formation (SFE, IMF, turbulence)
- Jets could also impact planet formation through disk irradiation/shielding and MHD effects
- Multiple components: stellar winds / magnetospheric /disk winds seem present: need detailed analysis and modeling
- Laboratory Astrophysics (HEDLA) is new powerful tool to study and model RMHD jets
The next step

- ALMA + nIR IFUs: crucial to resolve jet rotation profile, shocks, chemical stratification in statistical jet sample
- nIR interferometry of CTTS (e.g., PIONEER): powerful test of atomic jet models
- Synchrotron with eVLA, LOFAR: jet B-field
- Monitoring of shortest quasi-period ≈3-15yr to clarify origin
- Identify observational diagnostics of outflow-driven turbulence
- Broaden Laboratory Astrophysics to other flows (e.g., cometary globules, hot Jupiters)
Jet magnetic field

- Synchrotron linear polarisation:
  - B aligned with jet in HH80-81

- Synchrotron knot in DG Tau (see poster by Ainsworth et al.)
  - More to come with eVLA, LOFAR

Multi-Epoch HST HH Jet Studies

- **Main Results** (Hartigan et al 11, Bally)
  - Deflection shocks, Cavities, entrainment
  - Clumps!
  - Intersecting shocks, Mach Disks, sheets

1994.6  1997.6  2007.6
Episodic Ejections

Additional collimation by trapped magnetic fields

(Ciardi et al 09, Lebdev et al 10)