Observations and models of solar coronal jets

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Jets: ubiquitous phenomena

- Impulsive, collimated, sharp edged features
- Observed all over the atmosphere
  - in coronal holes
  - in active regions
- Observed over a broad range of scales
  - Coronal jets (macrospicules): X-ray, UV, White light
    - Length $> 10^4$ km
  - Chromospheric jets (surges): Ha, Ca II, UV
    - Length: $\sim 10^3$ km
  - Photospheric jets / spicules:
    - Length $< 10^3$ km
- Homologous recurring structures
Helical properties of jets

- Helical structure commonly observed
  - Morphology (e.g. Shibata et al. 92, Canfield et al. 96, Liu et al. 10, 11, Shen et al. 11, ...)
  - Doppler (imaging) (Harrison et al. 01, Jibben et al. 04, Young et al. 14, 15, Cheung et al. 15)
  - Stereoscopy (Patsourakos et al. 08, Kamio et al. 10, Matsui et al. 12)
- Twisting motion observed at all scales (e.g. Liu et al. 09, 11, Curdt et al. 11, 12, DePontieu et al. 12)
Magnetic field properties

- Jets generally (~90%) associated with multipolar fields. (Shimojo et al, 98,09)
- Jet collimated along “open” B lines:
- Jets occur at the interface of two connectivity domains:
- close & “open” = two different characteristic length of B gradients
  - Necessary ingredients for jets

(Liu et al. 11)
Magnetic field topology

- **Jets usually associated with 3D null points**
  - “Anemone” morphology (e.g., Shibata et al. 92, Liu et al. 11)
  - Few extrapolation cases (Fletcher et al. 01, Moreno-Insertis et al. 08, Liu et al. 11, Zhang et al. 12)
- **More complex topologies:** Guo et al. 13, Schmieder et al. 13

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12th Postdam Thinkshop, Germany - 27/10/15 - Solar jets - Etienne PARIAT
Jet progenitor and trigger

- Observations of sigmoid structure (Raouafi et al. 10, 12) and of small scale filaments (Kayshap et al. 13, Sterling et al. 15) prior to the jet

→ indication for pre-jet twisted flux rope in the closed field domain

- Flux rope recently found bellow null points (Jiang et al. 14, Kai et al. 15, Liu et al. 15, Masson et al. 16)

- Pre-jet photospheric motions generally convergent, i.e. magnetic cancellation filaments (Chen et al. 08, Chifor et al. 08, Guo et al. 13, Young et al. 14, Muglach et al. 15)
  - Flux emergence earlier (and necessary) but not directly linked with jet trigger
Evidence for magnetic reconnection

- X-ray jets: energetic events ($10^{20}-10^{22}$J).
  - Energy source must be magnetic

- Transient impulsive events:
  - Violent energy release

- **Obs. of non-thermal particles** (Bain et al. 09)

- X-ray jets associated with small flares: X-ray bright points (Shibata et al. 1992, 1994, ...):
  - Correlation between energies and plasma temperatures of the jet and of the flare
  - Area of footpoint flare corr. jet temperature

- Change of the coronal loops connectivity

- **Null points are preferential recon. sites**

- Numerous numerical simulations involving reconnection producing jets
Mechanism for jets (in 2D)

- Jet = flare involving strongly asymmetric field lines
- Jet bright point: standard post flare loop
- Jet: non-standard post flare loop
  - Energy deposit close to base of a extended loop
  - Transfer of energy along the extended loop
Jets and particles acceleration

- **Evidences of non-thermal e- beam during (large) jet events** (Aurass 94, Raulin 96, Bain et al. 09, Krucker et al. 11)
- **Test particle simulations (B fixed)**
  - at 3D null point (Dalla & Browning 05,06,08)
  - with relativistic e- (Rosdahl & Galsgaard 10)
- **Toward self-consistent model: PIC** (Baumann et al. 13)
  - Important tool to follow particle injection in the heliosphere and ribbon formation
Evaporation flows

- Deposition of energy following reconnection
- Upflow of material: \[ V_{Jet} \propto C_s \]
- Driver: additional gas pressure and thermal conduction

Shimojo & Shibata, 00

No heat conduction

(Miyagoshi & Yokoyama 04)

Reconnection Jet

Shimojo et al. 01

Evaporation Jet
Evaporation flow

- Relative good fits \((V, \rho, T)\) with observations (e.g. Shimojo et al 01, Chifor et al. 08, Matsui 12)
  - Velocity agreement at high Temp. (Matsui 12)
  - No good fit at lower temperature
  - Exponential intensity decrease with height in X-ray
- Jet properties depend on the energy deposit height, i.e., reconnection evolution
  - Mechanism different in the corona and in the chromosphere
Magnetic untwisting flows

- Magnetic Twist flows
  - Recon. of twisted/sheared and untwisted/unsheared loops
  - Release of the shear $\rightarrow$ non linear Alvénic wave
  - Driver: Kink-type wave magnetic pressure
Helical jet = destroyed erupting flux rope

- Helical jets corresponds to destroyed erupting flux rope (Moore et al. 10, Raouaffi et al. 12, Moreno-Insertis et al. 13, Archontis et al. 13, Kayshap et al. 13, Fang et al. 14, Lee et al. 15, Pariat et al. 15)

- Jet driver: untwisting of the reconnected field lines of the disrupted flux rope (Pariat et al. 09,10,15, Törok et al. 09, Moore et al. 10,13)

- Trigger of helical jets = trigger of coronal mass ejection
3D model of magnetic untwisting flows

- Helical jet formed by the sequential reconnection of field lines (Pariat et al.09,10,15; Török et al. 09; Dalmasse et al.12, Fang et al. 15, Lee et al. 15)
  - → 3D helical structure
  - Pref. obs. at lower temp. (e.g. 304A)
- 2 types of concomitant flows
  - Untwisting flows (low/warm temperature)
  - Evaporation flows (hot temperature)
Homologous property

- Magnetic system quasi relax to its initial potential state
- Continuous energy injection
- Null point configuration can simply produce multiple jets
  - Homologous system
    - Helicity release: jets
    - Relaxation & energy storage

(Pariat et al. 10)
Influence of inclination

• Parametric study of the influence of the inclination, $\theta$, of the coronal field
  – $1^\circ < \theta < 20^\circ$

• Helical jet always generated in that range of angle
  – Direction of the blowout jet is given by the inclination $\theta$ as for observations
  – Morphology of blowout jet is very similar, i.e. indep. of $\theta$

• Trigger energy strongly decreases with increasing $\theta$
  • $E_{\text{trig}}(20^\circ) = 60\% E_{\text{trig}}(1^\circ)$
  – Axisymmetric system able to store more energy
  – Thus shall generate more energetic jets

(Pariat et al.15)
Recent observations/models allow to strongly focused our understanding of coronal jets:

- **2 main reconnection-induced mechanisms:** evaporation & untwisting flows
  - Occurring concomitantly
  - Responsible for the ≠ obs. properties
  - **Relative importance/interplay of each mechanism to be understood:**
    - Relative energy distribution/transfer
    - Dependence on environmental conditions
    - No simulation is yet able to include processes

More evidences that jets and eruptions share same type of initial condition / trigger mechanisms

- **(Helical) jets = reconnection-destroyed erupting structures/CMEs**
  - Same problematic than flare/eruption init.

Coronal jet study: helps to understanding of chromospheric jet/spicules?
Thanks for your attention