Radio Jets in Young Stellar Objects

Guillem Anglada (IAA-CSIC, Spain)

Luis F. Rodríguez (CryA-UNAM, Mexico)
Carlos Carrasco-González (CryA-UNAM, Mexico)
Astrophysical Jets

Jets are ubiquitous in Astrophysics
Jets in YSOs

Jets are intrinsically associated to the SF process.

**Disk-jet scenario** valid in the formation of stars of all masses.

Gas entrained by the jet produces molecular outflows.

I will concentrate in the ionized jet component.
Jets in YSOs

Jets are intrinsically associated to the SF process.

Radio emission from YSOs traces the “base” of the jets, which is usually hidden at other wavelengths.
Examples of Radio Jets in YSOs

- SERPENS
- HH 1-2
- NGC2071-IRS3
- IRAS 16547-4247

Low Mass:
- 1000 AU
- 400 AU

Intermediate Mass:
- 3600 AU

High Mass:
- 5000 AU
- 15000 AU

References:
- Curiel et al. 1993
- Martí et al. 1993
- Carrasco-González et al. 2012
- Rodríguez et al. 2000
- Rodríguez et al. 2008
- Cepheus A 3.6 cm

Characteristics of Thermal Radio Jets

- Elongated morphology, indicating collimation at small scales (< 100 AU).
- Association with both high- and low-luminosity objects.
- Alignment within a few degrees with the large-scale outflow.
- Weak sources, with typical flux densities 0.01-1 mJy.
- Velocities of a few 100 km/s.
- Dynamical time scales of only a few years (extremely young material).
- Ionization starts at $r_0 < 10$ AU.
- Positive or flat spectral indices. Well described by thermal free-free jet models of Reynolds (1986): $S_\nu \propto \nu^{1.3-0.7/\epsilon}$, $\theta_\nu \propto \nu^{-0.7/\epsilon}$ ($w \propto r^\epsilon$, $\epsilon=1$ for a conical jet).

### Table 1: Properties of Selected Angularly Resolved Radio Jets in YSOs

<table>
<thead>
<tr>
<th>Source</th>
<th>$L_{bol}$ ($L_\odot$)</th>
<th>$M_*$ ($M_\odot$)</th>
<th>$d$ (kpc)</th>
<th>$S_\nu$ (mJy)</th>
<th>$\theta_0$ (deg)</th>
<th>Size (AU)</th>
<th>$V_j$ (km s$^{-1}$)</th>
<th>$t_{dyn}$ (yr)</th>
<th>$\dot{M}<em>i$ ($M</em>\odot$ yr$^{-1}$)</th>
<th>$r_0$ (AU)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH 1-2 VLA1</td>
<td>20</td>
<td>~1</td>
<td>0.4</td>
<td>1</td>
<td>0.3</td>
<td>19</td>
<td>200</td>
<td>2</td>
<td>0.7 $\times 10^{-8}$</td>
<td>$\leq 11$</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>NGC 2071-IRS3</td>
<td>~500</td>
<td>4</td>
<td>0.4</td>
<td>3</td>
<td>0.6</td>
<td>40</td>
<td>200</td>
<td>4</td>
<td>1 $\times 10^{-7}$</td>
<td>$\leq 18$</td>
<td>5, 6, 2, 7</td>
</tr>
<tr>
<td>Cep A HW2</td>
<td>$1 \times 10^4$</td>
<td>15</td>
<td>0.7</td>
<td>10</td>
<td>0.7</td>
<td>14</td>
<td>400</td>
<td>3</td>
<td>0.9 $\times 10^{-7}$</td>
<td>$\leq 60$</td>
<td>8, 9, 10, 11, 12</td>
</tr>
<tr>
<td>HH 80-81</td>
<td>$2 \times 10^4$</td>
<td>15</td>
<td>1.7</td>
<td>5</td>
<td>0.2</td>
<td>34</td>
<td>1500</td>
<td>7</td>
<td>0.6 $\times 10^{-6}$</td>
<td>$\leq 25$</td>
<td>13, 14, 15, 16, 17, 18</td>
</tr>
</tbody>
</table>

$^a$ Assumed.
Jets in All Phases of Stellar Formation

CLASS 0 OBJECT

(Reipurth et al. 2002)

TRANSITIONAL DISK

(Rodríguez et al. 2007, Tang et al. 2012)
Jets Across the Stellar Mass Spectrum

**JETS IN HIGH MASS PROTOSTARS**

IRAS 16547-4247
3.6 cm

(Rodríguez et al. 2008)

**OUTFLOWS IN PROTO-BROWN DWARFS**

(Lee et al. 2013)

(Palau et al. 2012)

IRAS 16547-4247
3.6 cm

(CO 3–2)

L328-IRS

J041757

3.6 cm 350 μm

 greyscale: CAHA–H

(0.06 pc)

27°41'10"

27°41'00"

4h17m58s.0 57°0
Emission from YSO radio jets is thermal free-free emission from partially ionized material.

Unlike HII regions, photoionization is not a viable ionizing mechanism, at least for objects of low bolometric luminosity.

(Anglada 1995)
Bolometric Luminosity, Outflow, and Radio Continuum Correlations

These correlations (Anglada 1995, 1996) are consistent with the predictions of a simple model of SHOCK IONIZATION (Curiel et al. 1987, 1989).

Correlations hold for jets of both LOW (very low?) and HIGH LUMINOSITY objects.

Can be used to discriminate between jets (earlier stage), that should fall on the correlations, and UCHII regions (later stage) that should fall near the Lyman line.
Radio Recombination Lines

Radio jets are expected to show radio recombination lines (RRLs). In combination with proper motions should provide 3D kinematics. Assuming LTE and a standard biconical jet, at cm wavelengths, it can be shown that the expected line to continuum flux ratio is:

\[
\frac{S_L}{S_C} = 0.19 \left( \frac{v_L}{\text{GHz}} \right)^{1.1} \left( \frac{T}{10^4 \text{ K}} \right)^{-1.1} \left( \frac{\Delta V}{\text{km s}^{-1}} \right)^{-1} (1 + Y^+)^{-1}
\]

(Y^+ = He^+/H^+)

RRLs from a jet are expected to be wide (~100 km/s), and therefore weak at cm wavelengths (\(S_L/S_C \sim 0.02\)).

So far, there are no detections of RRLs in jets at the expected LTE level. Broad radio recombination maser lines (flux density ~5 larger than LTE) have been detected toward the Ceph A HW2 jet (Jiménez-Serra et al. 2011).

More sensitive observations are needed to start using RRLs as tools to study jet kinematics.
Non-thermal Emission of YSO Jets

Emission from YSO radio jets is dominated by thermal free-free emission. However, negative spectral indices have been found in some radio knots, that usually appear in pairs, moving away from the central protostar at velocities of several hundreds of km/s.

These negative spectral indices have been interpreted as indicating non-thermal synchrotron emission from a small population of relativistic particles that would be accelerated in the ensuing strong shocks.

(Curiel et al. 1993)
Non-thermal Emission of YSO Jets

Detection of linearly polarized emission from the HH 80-81 jet, with the VLA, provided conclusive evidence for the presence of synchrotron emission in a YSO jet.

Allowed for the first time the direct measure of the magnetic field strength and morphology.

Measuring linear polarization in YSO jets is difficult because it is only a fraction of the total emission. Ultrasensitive radio interferometers, such as the SKA, will allow to detect and image the magnetic field in a large sample of YSO jets.

(Carrasco-González et al. 2010)
Non-thermal Emission of YSO Jets

New images with the Expanded VLA reveal fine details of the HH80 jet, emphasizing the differences and similarities between YSO jets and relativistic extragalactic jets.

(Carrasco-González et al., in prep)

In combination with the physical parameters (density, temperature, velocity) derived from the thermal component, the magnetic field will help in understanding YSO jet acceleration and collimation mechanisms, that appear to be similar for all kinds of astrophysical objects.
Expectations for SKA Observations

**BAND 5**, providing the highest frequency and angular resolution, appears as the most suitable option to study YSO jets, given their rising spectrum and compact size.

- **Survey of radio jets in YSOs** (will detect and accurately trace the position of deeply embedded YSOs)
  
  **Proto-brown dwarfs:**
  
  $d=500 \text{ pc}, \nu=10 \text{ GHz}, S_{\nu}=12 \mu\text{Jy} \Rightarrow S/N=10 \text{ with } t=20 \text{ min (SKA1-mid)}$
  
  $d=300 \text{ pc}$ would be reached in SKA1-mid “Early Science”.

  **Massive protostars:**
  
  $S_{\nu} d^2=10-100 \text{ mJy kpc}^2 (L_{bol} \text{ correlation}) \Rightarrow S/N>10 \text{ with } t=20 \text{ min in ALL THE GALAXY with SKA1-mid}$

  (in most of the galaxy in “Early Science”)
High angular resolution studies

Observations at different frequencies across Band 5 (14-5 GHz) can reach beam=30-80 mas, and would allow:

- To determine the variations of the physical parameters along the jet axis.
- To image the region around the injection radius of the ionized gas.
- To separate the jet free-free emission from the dust emission of large dust grains in the disk.

Problem: Sensitivity will be several times worst than for natural weighting (beam=1″-3″) ➔ Only relatively “strong” jets could be studied, unless the antenna configuration is changed to favor longer baselines.
• **3D kinematics using RRLs**

For $S_{\nu}(\text{cont})=3$ mJy, $\nu=10$ GHz, $T=10^4$ K, $\Delta V=100$ km/s ⇒

$S_{\nu}(\text{cont})/S_{\nu}(\text{line})=0.022$ ⇒ $S_{\nu}(\text{line})=75$ $\mu$Jy ⇒ $S/N=6$ with $t=1$ h (SKA1-mid and coarse spectral resolution).

Stacking of RRLs (35 RRLs in band 5) can improve $S/N$ by a factor of 6.

**Full potential with SKA Phase 2**: Proper motions (from continuum observations) + mapping of radial velocity (RRLs) ⇒ 3D jet kinematics.
• Search for linear polarization

Linear polarization detectable with SKA1-mid in jets with relatively bright non-thermal knots:

\[ S_\nu(\text{knot})=100 \, \mu\text{Jy}, \text{Pol. degree}=10\% \implies S/N=10 \text{ with } t=30 \text{ min}. \]

With SKA Phase 2 it will be possible to determine the structure and strength of the magnetic field in an extended sample of YSO jets.

YSO jets have the advantage that most of their emission is thermal and it can be used to derive the jet physical parameters (except the magnetic field). If the magnetic field is measured from the non-thermal component, then a full characterization of YSO jets would be obtained.

This would provide key information to help us to understand the formation mechanism of all astrophysical jets.
Radio Jets in Young Stellar Objects

Guillem Anglada (IAA-CSIC, Spain)

Luis F. Rodríguez (CRyA-UNAM, Mexico)
Carlos Carrasco-González (CRyA-UNAM, Mexico)