[Fe II] Outflows from Young Stars

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This presentation is based on the following publications

Itoh et al. *A Pair of Twisted Jets of Ionized Iron from L1551 IRS 5*, 2000, PASJ, 52, 81
Introduction: Outflows

Outflows from Young Stars

Directly driven outflows are believed to play an important role in removing angular momentum from a young star-disk system.

cf. Shock accelerated outflows
   Entrained gas by bow shock fronts
   Turbulence entrained gas in a shear layer
## Introduction: Outflows

<table>
<thead>
<tr>
<th>Outflow</th>
<th>Observational Evidence</th>
<th>Velocity (km/s)</th>
<th>Scale (AU)</th>
<th>Mass Loss Rate (M⊙/yr)</th>
<th>Collimation</th>
<th>Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical Jets</td>
<td>[S II], [O I], [N II], [Fe II], Hα, H₂</td>
<td>100–400</td>
<td>10³–10⁶</td>
<td>10⁻⁸–10⁻⁶ (10% ion. fr.)</td>
<td>Good</td>
<td>Many Class 0 &amp; I. Some Class II</td>
</tr>
<tr>
<td>HH flows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Jets</td>
<td>Thermal continuum</td>
<td>–</td>
<td>10–10²</td>
<td>&lt;10⁻⁷–10⁻⁵</td>
<td>Good</td>
<td>Some Class 0 &amp; I</td>
</tr>
<tr>
<td><strong>Winds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T Tauri Wind</td>
<td>P Cygni absorptions of Hα, Na D, Ca II, Mg II</td>
<td>50–200</td>
<td>&gt; 0.1</td>
<td>10⁻⁸–10⁻⁷</td>
<td>Unresolved</td>
<td>All Class II</td>
</tr>
<tr>
<td>Forbidden EL</td>
<td>[S II], [O I], [N II], [Fe II]</td>
<td>5–20 (LVC) (50–100 HVC=Jet)</td>
<td>&gt; 0.1</td>
<td>&lt; 10⁻⁷</td>
<td>Unresolved</td>
<td>All Class II</td>
</tr>
<tr>
<td>High Velicity Neutral Wind</td>
<td>Radio OH &amp; HI</td>
<td>50–200</td>
<td>10⁴–10⁶</td>
<td>10⁻⁸–10⁻⁷</td>
<td>Moderate</td>
<td>A few Class I</td>
</tr>
<tr>
<td><strong>Molecular Outflows</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classical Bipolar MO</td>
<td>CO</td>
<td>1–30</td>
<td>10⁴–10⁶</td>
<td>10⁻⁷–10⁻⁶</td>
<td>Poor</td>
<td>All Class O &amp; I. Some Class II</td>
</tr>
<tr>
<td>Extremely High V MO</td>
<td>CO, SiO</td>
<td>40–150</td>
<td>10⁴–10⁶</td>
<td>10⁻⁷–10⁻⁶</td>
<td>Moderate</td>
<td>Some Class 0 &amp; I. Some Class II</td>
</tr>
</tbody>
</table>
The [Fe II] $\lambda 1.644$ $\mu$m Emission

- Strongest forbidden line emitted from outflows in the near-infrared.
- Small extinction compared to optical forbidden lines. Suitable for embedded objects.
- High angular resolution available with AO.

Observations

Subaru Telescope (8.2 m) atop Mauna Kea

IRCS (Infrared Camera and Spectrograph)

Adaptive Optics system
The \([\text{Fe II}]\) emission traces outflows directly accelerated in the stellar vicinity as implied by its velocity of \(~300\text{ km/s}\) (cf. \(\text{H}_2\) lines).
# Observations: Targets

<table>
<thead>
<tr>
<th>Object</th>
<th>Date</th>
<th>Exposure (sec)</th>
<th>∆V (km/s)</th>
<th>Angular Resolution</th>
<th>P.A. (°)</th>
<th>AO</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1551 IRS 5</td>
<td>2000 Oct 16, 2002 Nov 26</td>
<td>720</td>
<td>59</td>
<td>0”.30</td>
<td>74</td>
<td>No</td>
</tr>
<tr>
<td>DG Tau</td>
<td>2001 Oct 31</td>
<td>320</td>
<td>30</td>
<td>0”.16</td>
<td>222</td>
<td>Yes</td>
</tr>
<tr>
<td>HL Tau</td>
<td>2001 Dec 25</td>
<td>2100</td>
<td>60</td>
<td>0”.50</td>
<td>51</td>
<td>Yes</td>
</tr>
<tr>
<td>RW Aur</td>
<td>2002 Nov 26</td>
<td>960</td>
<td>30</td>
<td>0”.20</td>
<td>120</td>
<td>Yes</td>
</tr>
</tbody>
</table>
L1551 IRS 5: Two Jets

Two jets emanating from the binary (triple) protostars

Fridlund & Liseau (1998)

Rodríguez et al. (2003)
L1551 IRS 5: Jets

- **R band (HST)**: Fridlund & Liseau (1998)
- **I band (HST)**: Pyo et al. (2002)
- **[Fe II] 1.600 µm (HST)**: White et al. (2000)
L1551 IRS 5: [Fe II] Jets

H cont., [Fe II] 1.644 µm & H$_2$ 2.122 µm (Subaru)

Pyo et al. (2002); Itoh et al. (2000)
L1551 IRS 5: Preliminary Slit Scan Data

0″ 0″.3 0″.6 0″.9 1″.2
0″.618 X 5″.79 Slit
0″.3 interval
13 slit positions

Pyo et al. in preparation
Three radial velocity components separated in space and velocity:

**High Velocity Component**
- $V_r = 300 \text{ km/s}$ with $\Delta V \approx 40 \text{ km/s}$
- Peak at $\sim 4''$ (PHK2) from the VLA sources

**Low Velocity Component** (turned out to be the Southern Jet)
- $V_r = 100 \text{ km/s}$ with $\Delta V = 130-160 \text{ km/s}$
- Peak at $1''.2$ (PHK1) from the VLA sources

**Pedestal and Wing Component**
- $V_r = 30-230 \text{ km/s}$ with broad width
- Shock accelerated gas or a lower velocity wind?

The [Fe II] emission is entirely blueshifted with no rest velocity emission seen. 😋 Ambient gas is also flowing ($H_2$ and CO flows)
H$_2$ emission has a velocity lower than that of the PWC and shows acceleration, suggesting that the H$_2$ gas is accelerated by the PWC.

The PWC, in turn, is either accelerated by the HVC or a wind with a wider opening angle, i.e., surrounding the HVC.
L1551 IRS 5: Widths at PHK1

Pyo et al. (2005)
L1551 IRS 5: Widths at PHK2

Pyo et al. (2005)
L1551 IRS 5: Spatial Width

High Velocity Component
- Width=0″.78 deconvolved to 0″.58 (80 AU) at both PHK 1 & 2
- Well collimated Northern Jet

Low Velocity Component (PHK 1)
- Spatially narrow subcomponent ⇐ Well collimated Southern Jet
- Spatially wide subcomponent ⇐ Width=2″.84 (400 AU):
  unknown whether it is associated with northern or southern jet.

Wing Component
- Associated with Northern Jet
- Width=0″.93 deconvolved to 0″.77 (108 AU) at PHK 2
- Slightly wider (wider opening angle) than the HVC
L1551 IRS 5: X Ray Emission

$N_H < 2 \times 10^{22} \text{ cm}^{-2}$ $(A_V < 10 \text{ mag})$

$T_x = 0.5 - 5 \text{ keV} \ (T \sim 10^7 \text{ K})$

$L_x = 4 \times 10^{28} \text{ erg/s}$

The inclination corrected velocity of the HVC (440 km/s) is sufficient to produce a plasma at this temperature when it is thermalized.
DG Tau: Jet

H cont., [Fe II] 1.644 µm & H$_2$ 2.122 µm (Subaru)

Dougados et al. (2000)
DG Tau: HVC & LVC

Two radial velocity components distinctly separated in space and velocity:

High Velocity Component
- $V_r = 200 - 300$ km/s
- $\Delta V \approx 50$ km/s
- Peak at $0''.6 - 0''.8$ from DG Tau

Low Velocity Component
- $V_r = 50 - 150$ km/s
- $\Delta V \approx 100$ km/s
- Peak at $0''.2 - 0''.5$ from DG Tau

Counter Jet
- Gap = $0''.7$
- Disk radius = 140 AU

Pyo et al. (2003)

The presence of two components distinctly separated in space and velocity favors two physically different outflow interpretation (see comparison with models).
HL Tau: Jet

Mundt, Ray & Bührke (1998)

F675W (HST/WFPC), H & K (Subaru/CIAO)
Two radial velocity components are detected:

High Velocity Component
- $V_r \sim 180$ km/s
- $\Delta V \leq 40$ km/s
- Peaks at $\sim 0''.4$ & $\sim 1''.3$

Low Velocity Component
- $V_r \sim 50$ km/s as a broad (0-100 km/s) wing
- Peak close to the star

Counter jet
- Gap=$0''.8$
- Disk radius=160 AU
1. Continuum (star) and Br12 share the same sharp cutoff on the redshifted side.

2. The peak position of Br12 is shifted by 0″.038 to the blueshifted side. On the blueshifted side, Br12 has excess over scattered stellar Continuum.

3. The spatial profile of LVC is shifted by 0″.077 to the blueshifted side. It also shows excess over Continuum, although marginal.

4. HVC is separated away from the star.
1. Br12 arises mostly from the unresolved vicinity of the star, but part of its emission must originate at 5-10 AU away from the star.

2. Br12 arises also in the jet ~200 AU away from the star.

3. The dominant part of the [Fe II] LVC emission arises in the jet at ~15 AU away from the star. This length scale is too large for an acceleration region of a jet (considering its velocity).

4. The LVC may then be:
   - An outer, lower velocity part of a single wind (disk/X wind)
   - An independent low velocity outflow (like DG Tau)
   - The base of HVC under collimation (see comparison with models)
RW Aur: Jet

Dougados et al. (2000)
Two radial velocity components are detected:

**High Velocity Component**
- $V_r \sim 180$ km/s
- $\Delta V = 50$ km/s
- Peak at $\sim 0''.4$ from the star

**Low Velocity Component**
- A broad wing (0-100 km/s)
- Affected by a spurious feature

Counter jet is detected:
- No gap is seen
- Disk radius $< 20$ AU
- Velocity asymmetry
Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>HVC</th>
<th>LVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1551 IRS 5</td>
<td>Located farther away</td>
<td>LVC is part of the southern jet, but PWC is associated with the northern jet</td>
</tr>
<tr>
<td></td>
<td>Well collimated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$V_r \sim 300$ km/s, $\Delta V=40$ km/s</td>
<td>$V_r \sim 150$ km/s, $\Delta V=150$ km/s</td>
</tr>
<tr>
<td>DG Tau</td>
<td>Located farther away</td>
<td>Closer to the star as an independent component in velocity and space</td>
</tr>
<tr>
<td></td>
<td>$V_r \sim 250$ km/s, $\Delta V=50$ km/s</td>
<td>$V_r \sim 100$ km/s, $\Delta V=100$ km/s</td>
</tr>
<tr>
<td>HL Tau</td>
<td>Located farther away</td>
<td>Closer to the star but not coincident with it</td>
</tr>
<tr>
<td></td>
<td>$V_r \sim 180$ km/s, $\Delta V\lesssim 40$ km/s</td>
<td>$V_r =0-100$ km/s</td>
</tr>
<tr>
<td>RW Aur</td>
<td>Located farther away</td>
<td>Closer to the star</td>
</tr>
<tr>
<td></td>
<td>$V_r \sim 180$ km/s, $\Delta V=50$ km/s</td>
<td>$V_r =0-100$ km/s</td>
</tr>
</tbody>
</table>

Closer to the star as an independent component in velocity and space.
Shang et al. (1998): X wind model

For HL Tau and RW Aur, the overall shape of the model PVDs agrees with the observed ones, but the observations show:

HVC is much stronger than LVC
HVC is located away from the stellar position

For DG Tau, the model has difficulties to explain the spatial extent of LVC. Another wind (disk wind?) may be necessary.
Comparison with Models

Pesenti et al. (2003): Disk wind model

The model shows clearly separated two components and may be compared with the PVD of DG Tau.

However, the model does not reproduce the observed HVC characteristics such as its narrow velocity width and relatively constant velocity.

The model also has a difficulty to explain the spatial extent of the LVC of DG Tau and the observed electron density \((10^4-10^6 \text{ cm}^{-3})\).
Pesenti et al. (2003): Disk wind model

For HL Tau and RW Aur, the overall shape of the model PVD is similar to the observed ones, but the observations show:
- HVC is located away from the stellar position
- HVC is much stronger than LVC

For DG Tau, the model has difficulties to explain the spatial extent of LVC and its relative strength to HVC. LVC may be a disk wind and HVC (=Jet) may be a different outflow (X wind or another mechanism launched at inner regions).
Reconnection of magnetic lines of force in the solar flares produces a well collimated jet along open magnetic field lines with a velocity of several hundred km/s.
A reconnection wind model associated with dipolar magnetic field X-ray flares naturally produces two types of outflows emanating simultaneously from the vicinity of a young star.

Hayashi, Shibata & Matsumoto (1996)