 IMPORTANCE OF THE OUTFLOWS

I. Ubiquitous and essential together with the gravitational collapse.
II. Closely related to the accretion of disk material onto central star (dM_{outflow}/dM_{acc.} ~ 0.01)
III. Play an important role for removing angular momentum from accreting protoplanetary disk

The outflows provide us with crucial information for understanding the star forming process.

Evolution Stages of Low Mass Star

Outflow Structure [Imagination]

<table>
<thead>
<tr>
<th>V (km/s)</th>
<th>COLLIMATION</th>
<th>REMARK</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH JET</td>
<td>100 – 400</td>
<td>WELL (PI) gas (HVC)</td>
</tr>
<tr>
<td>RADIO JET</td>
<td>–</td>
<td>WELL</td>
</tr>
<tr>
<td>T Tauri FEL</td>
<td>50 – 100</td>
<td>UNRESOLVED</td>
</tr>
<tr>
<td>T Tauri WIND</td>
<td>50 – 200</td>
<td>UNRESOLVED</td>
</tr>
<tr>
<td>HVNW</td>
<td>50 – 200</td>
<td>MODERATE</td>
</tr>
<tr>
<td>‘CLASSICAL’ CO</td>
<td>1 – 30</td>
<td>POOR</td>
</tr>
<tr>
<td>EV</td>
<td>40 – 150</td>
<td>MODERATE</td>
</tr>
</tbody>
</table>

* PI = Partially Ionized  "V" (Electron Density)
**Classical** molecular outflows

- $V \sim 1 - 20$ km/s
- Two separate lobes of gas. The axes of the lobes are in perpendicular to the major axis of thick disk.
- Opening angle: 20 – 90 degrees
- Length/Width = 3 – 10
- Empty cavity structure
- Linear acceleration with distance from the central source

Snell, Loren, & Palmecke (1980)

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**Magnetocentrifugally driven winds**

- Acceleration $r < \text{Alfven radius ($r_A$)}$
- Collimation $r > \text{Alfven radius}$
- $\theta_0 < 30$ degrees

Pudriz & Norman (1983)

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**Mechanism of the Outflows**

- Magneto-hydrodynamic (MHD) models are favored as the physical mechanism, but...

- (1) X-wind : Disk Inner-edge
  (e.g. Shang, Shu, & Glassgold 1998)
- (2) Disk Wind : Broad range of disk radii (0.07 – 0.1 AU) (e.g. Pesenti et al. 2003)
- (3) Re-Connection (Flare)
  (e.g. Hayashi et al. 1996)

- The innermost region (<100 AU) = Acceleration and Collimation Area

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**How to access the innermost region?**

- I. High angular resolution with AO/SUBARU $0.1''(H) = 14$ AU @ TMC (d ~ 140 pc)
- II. Near Infrared wavelength : Large extinction close to central source
- III. [Fe II] and H2 emission lines
- IV. High Spectral Resolution w/ Echelle
- V. Position-Velocity Diagram

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**Telescope & Instruments**
Infrared Camera and Spectrograph (IRCS)

Camera Part
Infrared Slit Viewer
Grism Mode
Pixel Scale
0.02"/pixel
0.06"/pixel
Echelle Part
Spectral Resolution
20000 (15 km/s) ~ 5000 (60 km/s)
Pixel Scale
0.06" along slit length
Band
Iz --> M band (0.9 - 5.5 μm)

Grism Mode

Tokunaga et al. (1998), Kobayashi et al. (2000)

IRCS @ Cassegrain (before July 2005)
Operated very successfully for five years w/ current AO
- 0.9-5.5μm imaging (23mas/pix & 58mas/pix)
- 0.9-4.2μm Low-resolution spectroscopy (R=200-1000)
- 23mas/pix & 58mas/pix
- 0.9-5.5μm High-resolution Echelle spectroscopy (R=5000-20000)
- 60 mas/pix along the slit length

IRCS @ Nasmyth (after Jan. 2006)
- 2006 Jan. First light on Nasmyth w/o AO
- 2006 May First light w/ NGS AO
- 2007 Mar. First light w/ LGS AO
- New functions
  - Coronagraph Mask (0'.1, 0'.2, 0'.3, 0'.6, 0'.9)
  - Polarization
  - Simultaneous Wide band spectroscopy (Prism) (R=50-100 @ 1.0-5.5μm)
  - High-spectral resolution spectroscopy (R=70000)

IRCS Science case
- Wide variety of Science Fields will be covered.
  - Solar System
  - Origin of the Satellites of Outer Planets
  - Extra Solar System and Its Formation
  - Formation and Evolution of Proto-planetary Disks
  - Chemical Evolution in Proto-planetary Disks
  - Origin of Jets and Outflows from YSOs
  - Stars
  - Outer Atmosphere of Late Type Stars
  - Interstellar Medium
  - Abundance Study of Fundamental Molecules
  - QSO & AGNs
  - Spectroscopic Study of Massive Black Holes in Nearby Starburst Galaxies
  - Direct Imaging and Spectroscopy of Quasar Host Galaxies
  - High-z Galaxies and Cosmology
  - Deep Fields with LGS AO
  - High-Dispersion Infrared Spectroscopy of High-redshift QSOs

LAYOUT of Subaru LGSAO

Improvement of spatial resolution by 188 element LGSAO
After reduction procedure

To fully extract spatial-velocity information

Data Reduction with IRAF

Two fold V. : (1) L1551 IRS 5

LVC : d ~ 1.2 – 2.3", V ~ -100 km/s, FWHM ~ 100 – 200 km/s
HVC : narrow & extended, d > 1.3", V ~-300 km/s, FWHM ~ 60 km/s
PWC, velocity increase from LVC to HVC

Two fold V. : (2) DG Tau

HVC : narrow & long, d > 0.8"
V~220 km/s, FWHM~ 50 km/s
LVC : V ~ 100 km/s, FWHM ~ 100 – 200 km/s,
d ~ 0.4"
0.7" Gap & Redshifted Outflow

Two fold V. : (3) HL Tau

HVC : Narrow and extended feature (V~180 km/s, FWHM~ 60 km/s)
LVC : Weak and compact (V ~ -60 km/s), Peak at Y = 0".1
Redshifted Jet : V~150 km/s, FWHM ~ 60 km/s, dAv ~ 9 mag.
Optically Thick Disk : Rproject ~ 100 AU

Two fold V. : (4) RW Aur

Blue Jet (HVC) : V~190 – 160 km/s (decrease), FWHM ~ 60 km/s
Red Jet : V ~ 95 – 135 km/s (increase), FWHM ~ 40 km/s
LVC : Weak and compact (V ~ 100 – 20 km/s @ Y < 0".4) (time variation)

Discussion: Launching Points

• HVC is launched from the star surface or its vicinity.
• LVC is launched from the inner edge of the accreting disk

V (outflow) ~ Keplerian velocity at their launching radius
(e.g. Kudoh & Shibata 1997, Königl & Pudritz 2000, Matt et al. 2003, etc.)
**Discussion**

**Two V components are clearly distinct in space and velocity**

- **HVC**: High velocity + Narrow velocity width
  - A well collimated jet launched from the star surface or its vicinity

- **LVC**: Low velocity + Broad velocity width
  - Widely opened disk wind launched from the inner edge of the accreting disk

**[1]** Two launching points:
  - What is heating mechanism for LVC?

**[2]** Two outflows Mechanisms:
  - (+ YSOs are X-ray sources.)
    - HVC: reconnection of the stellar magnetic field anchored to the disk
    - LVC: magnetocentrifugal force
      (Shu & Shang 1997; X-wind, Ferriera, 1997: Disk wind)

**Additional tasks**

- [1] What is physical relation between HVC and LVC?
  - Slit-scan or IFU imaging spectroscopy

  - [Fe II] Survey for Class I sources

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**L1551 IRS 5: PHK1**

**Widely Opened Wind**

(`PHK = Pyo, Hayashi, and Kobayashi`)

(Pyo et al. 2005)

**LVC at PHK1**

- LVC\textsubscript{wide} is not caused by the scattering
  - (1) Continuum dose not have wide component as wide as LVC.
  - (2) HVC does not show wide component.

- LVC\textsubscript{wide} is not from the bow shock wing or entrained gas.
  - overall constant velocity along the X

- LVC\textsubscript{narrow} and LVC\textsubscript{wide} has the same opening angle of ~100 degree.

- LVC\textsubscript{narrow} and LVC\textsubscript{wide} launched similar Alfven radius because they have the same velocity.

**LVC has widely opened wind which is filling the gap between the highly collimate HVC and the poorly collimated shell of CO outflow.**

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**L1551 IRS 5: PHK2**

**Two V components in N. Jet**

(Northern Jet has two velocity comp. (~270 km/s and ~140 km/s)

(HVC is a highly collimated jet: same spatial widths of 0.78” at both PHK1 and PHK2.)


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**Observed Raw Data of [Fe II] 1.644 um**

- 0”.618 X 5”.79 Slit
- 0”.3 interval
- 13 slit positions
-100 km/s component moving along the southern jet direction with keeping constant velocity

There is another a slower component along the northern jet in LVC.

Slit Scan L1551 IRS 5 (2)

- [Fe II] λ1.644 μm emission line observations toward L1551 IRS 5, DG Tau, HL Tau, and RW Aur with high angular resolution by using Subaru Telescope
- We showed that [Fe II] emission is a powerful tracer for fast jets and winds.
- For all objects we detected two distinct velocity components (HVC and LVC).
- Disks: DG Tau and HL Tau Rₚₑᵢ₅₉ ~ 100 AU
- Redshifted Jet: DG Tau and HL Tau within d < 1.5
- LVC of L1551 IRS 5 has wide spatial width.

Summary

1. [Fe II] λ1.644 μm emission line observations toward L1551 IRS 5, DG Tau, HL Tau, and RW Aur with high angular resolution by using Subaru Telescope
2. We showed that [Fe II] emission is a powerful tracer for fast jets and winds.
3. For all objects we detected two distinct velocity components (HVC and LVC) in space and velocity.
4. Disks: DG Tau and HL Tau Rₚₑᵢ₅₉ ~ 100 AU
5. Redshifted Jet: DG Tau and HL Tau within d < 1.5
6. LVC of L1551 IRS 5 has wide spatial width.