Study of Jets/Outflows from YSOs with IRCS/SUBARU

Tae-Soo Pyo
Subaru Telescope

March 17, 2006

Agenda

I. Introduction of Outflows

II. Introduction of IRCS

III. Research Results

IV. Discussion

V. Summary

Importance of the Outflows

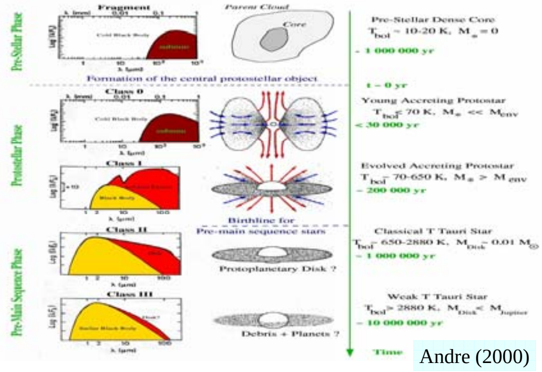
I. Ubiquitous and essential together with the gravitational collapse.

II. Closely related to the accretion of disk material onto central star ($dM_{outflow}/dM_{acc.} \sim 0.01$)

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



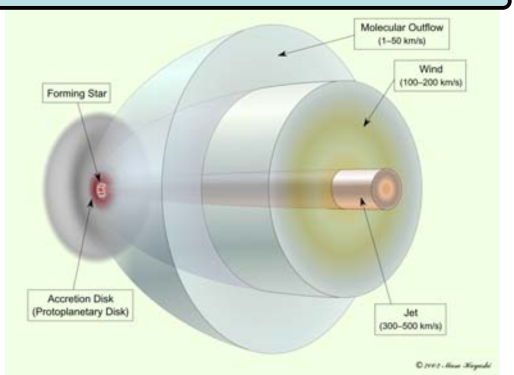
Andre (2000)

Young Stellar Outflows

	V (km/s)	Collimation	Remark
HH jet	100 – 400	Well	(PI) gas (HVC)
Radio jet	–	Well	PI gas
T Tauri FEL	5 – 20 (LVC) 50 – 100 (HVC)	Unresolved	PI gas LVC & HVC
T Tauri Wind	50 – 200	Unresolved	(Neutral?) Cold Gas
HVNW	50 – 200	Moderate	Neutral Gas
'Classical' CO	1 – 30	Poor	Entrained Gas
EHV	40 – 150	Moderate	Neutral Gas

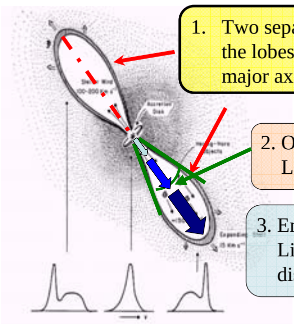
* PI = Partially Ionized

Outflow Structure [Imagination]



"Classical" molecular outflows

V ~ 1 – 20 km/s



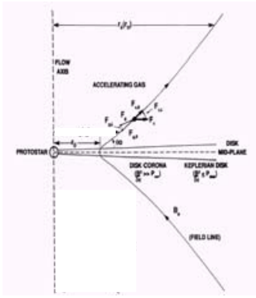
1. Two separate lobes of gas. The axes of the lobes are in perpendicular to the major axis of thick disk.

2. Opening angle : 20 –90 degrees
Length/Width = 3 ~ 10

3. Empty cavity structure
Linear acceleration with distance from the central source

Snell, Loren, & Plambeck (1980)

Magnetocentrifugally driven winds



Blandford & Payne (1982)

Acceleration
r < Alfven radius (r_A)

Collimation
r > Alfven radius

θ_0 < 30 degrees

Pudriz & Norman (1983)

Mechanism of the Outflows

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

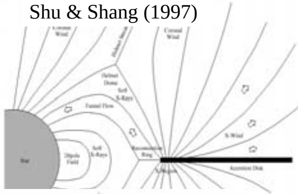
(1) X-wind : Disk Inner-edge
(e.g. Shang, Shu, & Glassgold 1998)

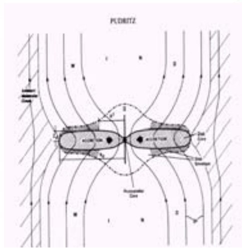
(2) Disk Wind : Broad range of disk radii (0.07 – 0.1 AU) (e.g. Pesenti et al.2003)

(3) Re-Connection (Flare)
(e.g. Hayashi et al. 1996)

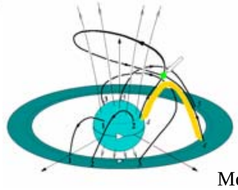
THE INNERMOST REGION (<100 AU)
= ACCELERATION AND COLLIMATION AREA

Shu & Shang (1997)





Pudriz & Norman (1983)
Pure disk wind model



Montmerle et al. (2000)

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

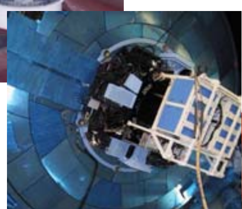
III. [Fe II] and H2 emission lines

IV. High Spectral Resolution w/ Echelle

V. Position-Velocity Diagram

Telescope & Instruments

Subaru Telescope (NAOJ)
8-m Tel. at Mauna Kea



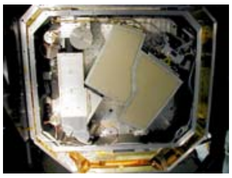
NIR [Fe II] emission
High spatial resolution
High velocity resolution

Adaptive Optics system

IRCS (InfraRed Camera and Spectrograph)

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)

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

IRCS @ Cassegrain (before July 2005)

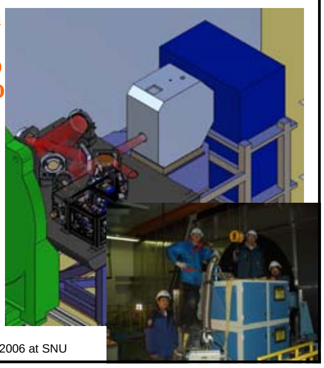
Operated very successfully for five years w/ current AO

- 0.9-5.5um Imaging
  (23mas/pix & 58mas/pix)
- 0.9-4.2um Low-resolution spectroscopy (R=200-1000)
  (23mas/pix & 58mas/pix)
- 0.9-5.5um 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 @ 1.0-5.5um)
- 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
- Formaton and Evolution of Proto-planetary Disks
- Chemical Evolution in Proto-planetary Disks
- Origin of Jets and Outflows from YSOs

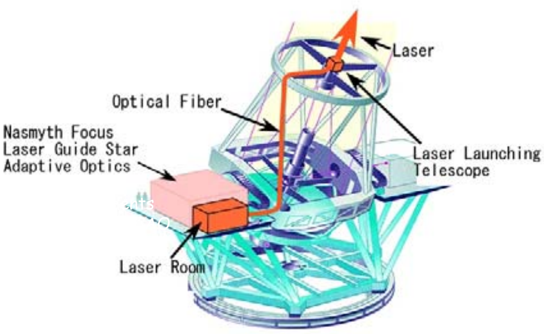
Stars
- Outer Atmosphere of Late Type Stars

Interstellar Medium
- Abundance Study of Fundamental Molecules

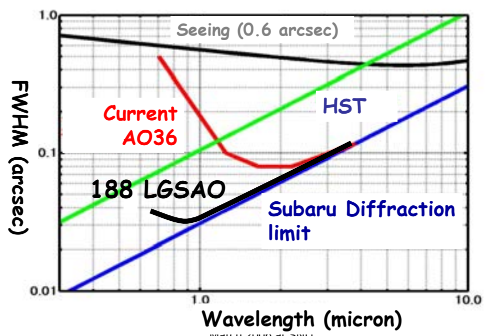
QSO & AGNs
- Spectroscopic Study of Massive Black Holes in Nearby Starburst Galaxies
- Direct Imaging and Spectroscopy of Quasar Host Galaxies

High-z Galaxies and Cosmology
- Deep Fields with LGS AO
- High-Dispersion Infrared Spectroscopy of High-redshift QSOs

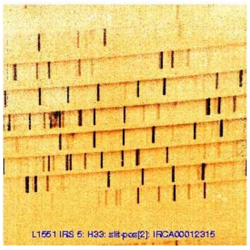
LAYOUT of Subaru LGSAO



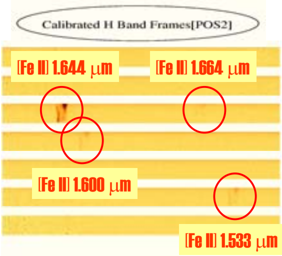
Improvement of spatial resolution by 188 element LGSAO



Data Reduction with IRAF



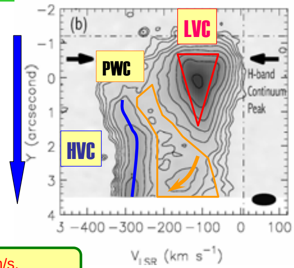
H band Spectra



After reduction procedure

Position-Velocity Map
To fully extract spatial-velocity information

Two fold V. : (1) L1551 IRS 5

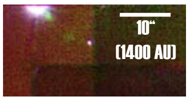


LVC : d ~ 1.2 – 2.0" , V ~ -100 km/s,
FWHM ~ 100 – 200 km/s
HVC : narrow & extended, d > 1.36"
V~-300 km/s, FWHM ~ 60 km/s
PWC: velocity increase from LVC to HVC

(Pyo et al. 2002, 570, 724)

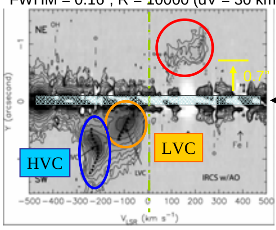
March 2006 at SNU 20

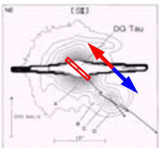
Two fold V. : (2) DG Tau



H-cont, [Fe II], H_2

FWHM = 0.16", R = 10000 (dV = 30 km/s)





Eislöffel & Mundt (1998)

(Pyo et al. 2003, ApJ, 590, 340)

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

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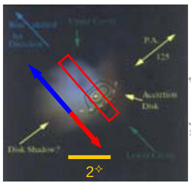
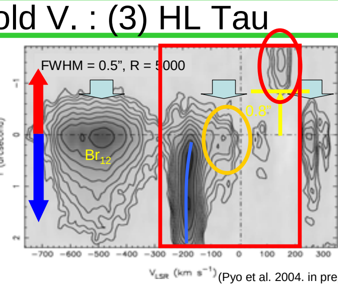
Two fold V. : (3) HL Tau



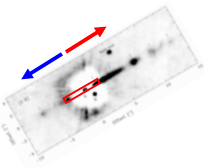
Close et al. (1997)



(Pyo et al. 2004. in preparation)

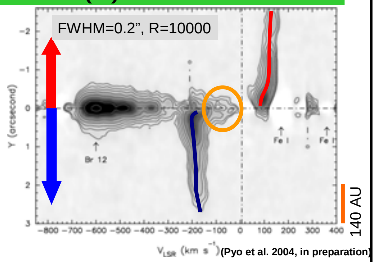
HVC : Narrow and extended feature (V~-180 km/s, FWHM~ 60 km/s)
LVC : Weak and compact (V ~ -60 km/s), Peak at Y = 0".1
Redshifted Jet : V~150 km/s, FWHM ~ 60 km/s , dAv ~ 9 mag.
Optically Thick Disk : $R_{project}$ ~ 100 AU

Two fold V. : (4) RW Aur



1997.Jan CFHT + PUEO

Dougados et al. (2000)



(Pyo et al. 2004, in preparation)

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)

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Discussion: Launching Points

	HVC (km/s)	LVC (km/s)	Inclination (º)	Keplerian Radius (AU)
L1551 IRS 5				
DG Tau				
HL Tau				
RW Aur		(very weak)	(López-Martin et al. 2003)	

• 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

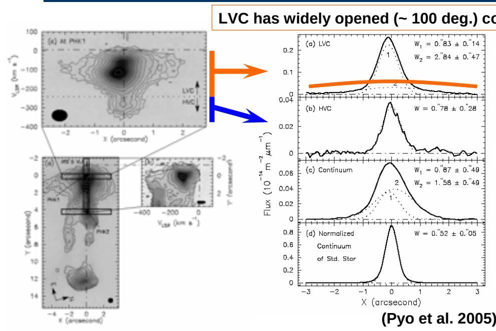
[1] Two launching points :
What is heating mechanism for LVC?
[2] Two outflows Mechanisms?
(+ YSOs are X-ray sources.)
HVC ← reconnection of the stellar magnetic field anchored to the disk
(Hayashi et al. 1996; Hirose et al. 1996;Goodson et al. 1997, 1999)
LVC ← magnetocentrifugal force
(Shu & Shang 1997:X-wind, Ferriera,1997:Disk wind)

Additional tasks

- [1] What is physical relation between HVC and LVC?
  → Slit-scan or IFU imaging spectroscopy
- [2] Universality of Two fold Velocity Structure.
  → [Fe II] Survey for Class I sources

L1551 IRS 5: PHK1 Widely Opened Wind

LVC has widely opened (~ 100 deg.) component



(Pyo et al. 2005)

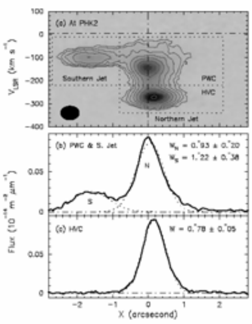
(* PHK = Pyo, Hayashi, and Kobayashi)

LVC at PHK1

- LVCwide is not caused by the scattering
  (1) Continuum dose not have wide component as wide as LVC.
  (2) HVC does not show wide component.
- LVCwide is not from the bow shock wing or entrained gas. ← overall constant velocity along the X
- LVCnarrow and LVCwide has the same opening angle of ~100 degree.
- LVCnarrow and LVCwide launched similar Alfven radius because they have the same velocity.

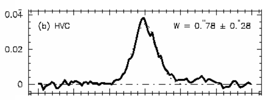
LVC has widely opened wind which is filling the gap between the highly collimate HVC and the poorly collimated shell of CO outflow.

L1551 IRS 5 : PHK2 Two V components in N. Jet



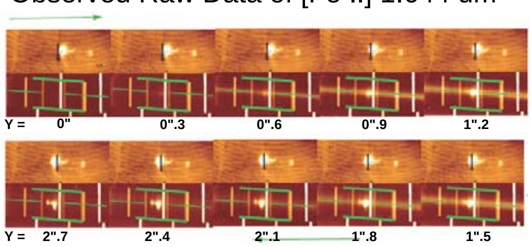
Northern Jet has two velocity comp. (~270 km/s and ~ 140 km/s)

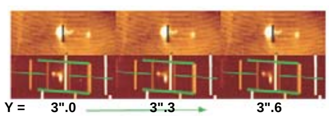
HVC is a highly collimated jet : same spatial widths of 0.78” at both PHK1 and PHK2.



(Pyo et al. 2005, ApJ)

Observed Raw Data of [Fe II] 1.644 um



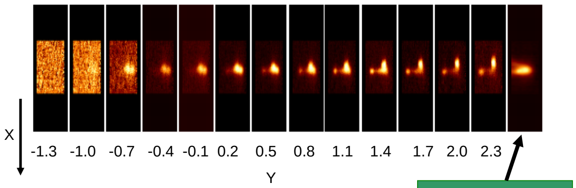


0".618 X 5".79 Slit

0".3 interval

13 slit positions

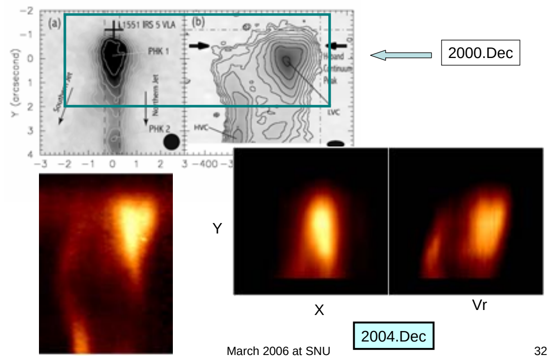
Slitscan of L551 IRS 5(1)



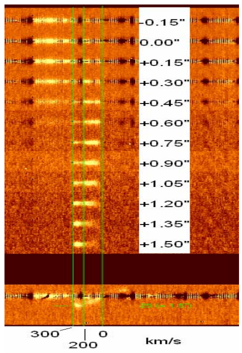
-100 km/s component
: moving along the southern jet direction
with keeping constant velocity

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

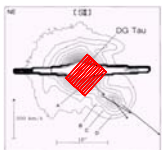
Slit Scan L1551 IRS 5 (2)



Slit Scan Observation: DG Tau



[1] 3-D Space-Velocity Map
[2] radial velocity for entire region
[3] Channel Map at each V region :
spatial distribution



Eislöffel & Mundt (1998)

(in preparation)

Summary

1. [Fe II] λ 1.644 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.
   → Two outflow mechanisms, heating mechanisms
4. Disks: DG Tau and HL Tau $R_{project}$ ~ 100 AU
5. Redshifted Jet : DG Tau and HL Tau within d < 1".5
6. LVC of L1551 IRS 5 has wide spatial width.