Study for Origin and Structure of Outflows from YSOs: [Fe II] 1.644 μm Spectroscopy with High Angular Resolution

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I. Introduction: Young Stellar Outflows

- Ubiquitous in star formation
- Closely related to the accretion process
- Play an important role for removing angular momentum from a star-disk system

→ Studies of YSO outflows may provide us with crucial information for understanding the physical process of star formation.

I. Introduction: Observations of YSOs

We can resolve the structure within 100 AU from the source, where collimation and acceleration are occurred.

- •Collimation Mechanism
- •Acceleration Mechanism
- •Launching Mechanism

High (Spatial + Velocity) Resolution

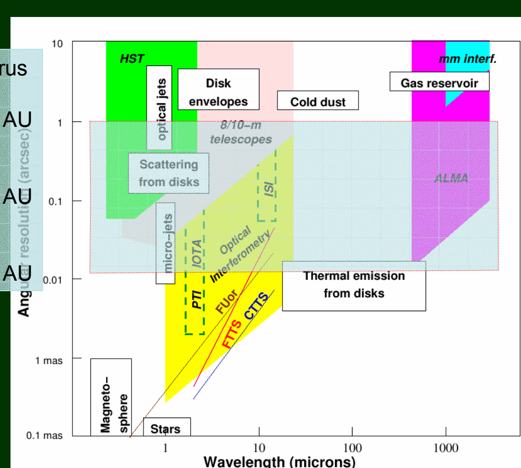
→ AO + IRCS (Echelle)

Taurus

140 AU

14 AU

1.4 AU



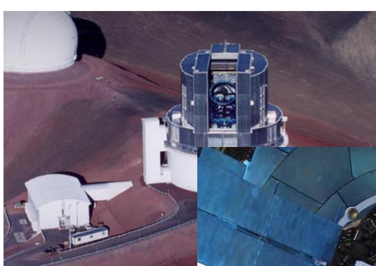
Malbet (2003)

I. Introduction: NIR [Fe II] Emission Lines

1. The strongest forbidden lines in the near-infrared
2. Small extinction
3. Trace partially ionized region & shocked region
   (Ionization Energy of Fe I : 7.6 eV)

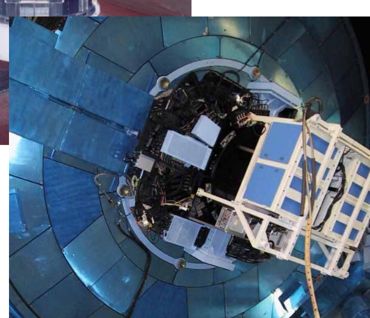
Near Infrared [Fe II] emission lines will be a good tracer for outflows in the vicinity of the young stellar objects.

II Observations

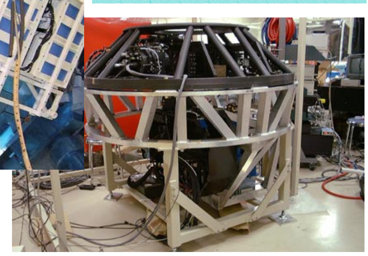


Subaru Telescope

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



Adaptive Optics system



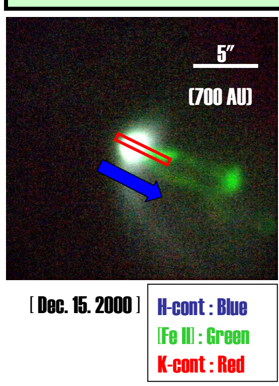
Infrared Camera and Spectrograph

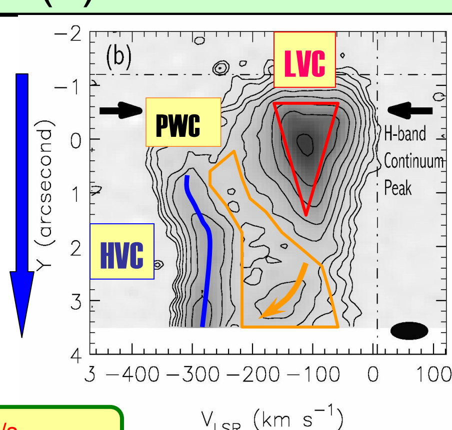
Sub-arcsecond Workshop @ NAOJ Feb.17-19. 2004

II Observations

Object	Obs. Date (mm/dd/yyyy)	Exp. Time (sec)	R (dV) (km/s)	Spatial Res. (″)	P.A. (°)	AO
L1551 IRS 5	10/16/2000	720	59	0.30	74	×
DG Tau	10/31/2001	320	30	0.16	222	○
HL Tau	12/25/2001	2100	60	0.50	51	○
RW Aur	11/26/2002	960	30	0.20	120	○

III. Results : (1) L1551 IRS 5



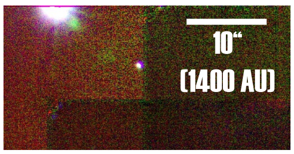


(Pyo et al. 2002)

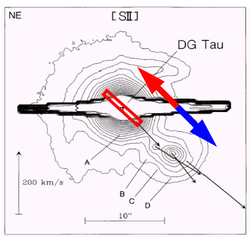
LVC : d ~ 1.2 – 2.0" , V ~ -100 km/s,
FWHM ~ 100 – 200 km/s
HVC : narrow & extended, d > 1.36"
V~-300 km/s, FWHM ~ 60 km/s
PWC: velocity increase from LVC to HVC

Sub-arcsecond Workshop @ NAOJ Feb.17-19. 2004

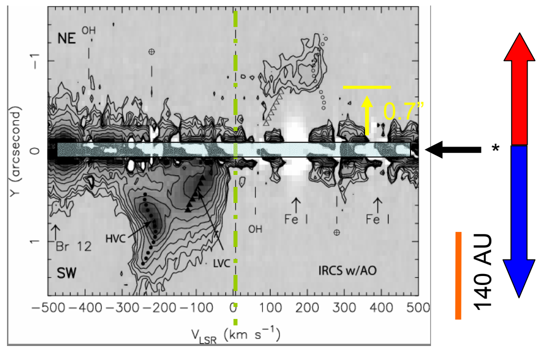
III. Results: (2) DG Tau



H-cont, [Fe II], H_2



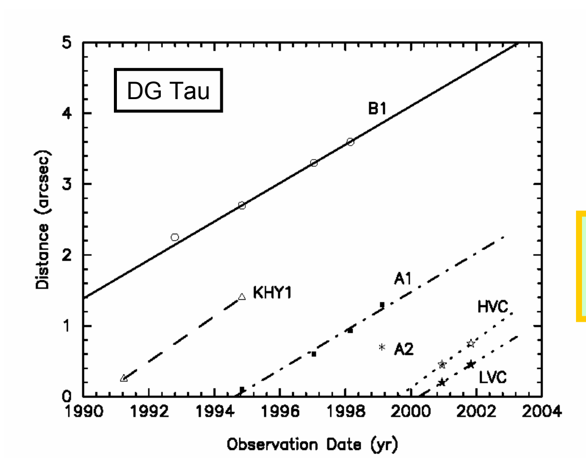
Eislöffel & Mundt (1998)



(Pyo et al. 2003)

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

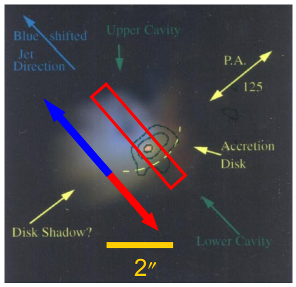
(2)DG Tau: Ejection of Knots



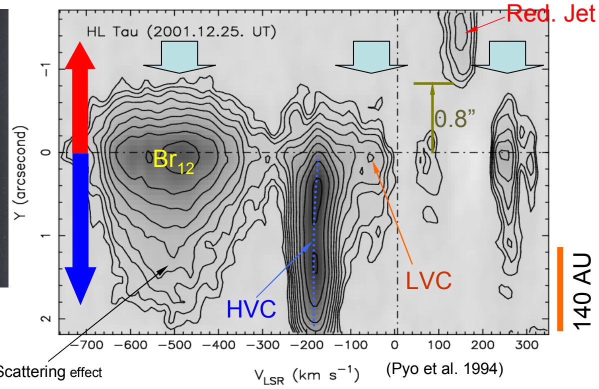
Proper motion
~ 0.27 "/yr

Ejection period
~ 5 yrs

III. Results: (3)HL Tau



Close et al. (1997)



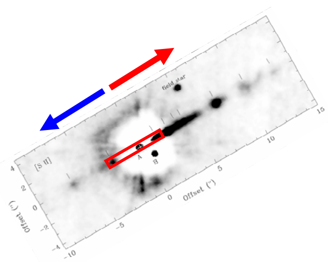
HVC : Narrow and extended feature (V~-180 km/s, FWHM~ 60 km/s)

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.

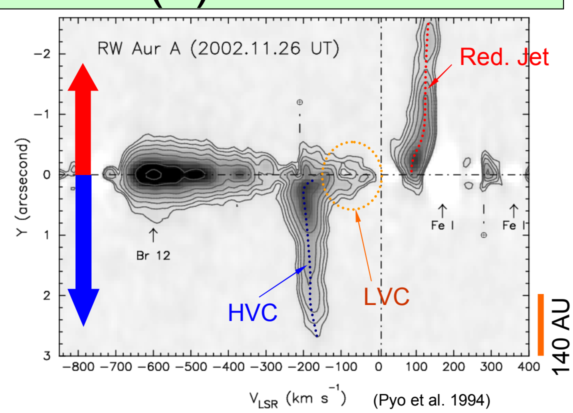
Optically Thick Disk : $R_{project}$ ~ 100 AU

III. Results: (4)RW Aur



1997.Jan CFHT + PUEO

Dougados et al. (2000)



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: Velocity & Launching Points

	HVC (km/s)	LVC (km/s)	Inclination (°)	Keplerian Radius (AU)
L1551 IRS 5	~ 430	~ 140 (very strong)	~ 45 (Stock et al. 1988)	HVC →0.05 – 0.1 (~ a few x R_*) LVC →0.2 – 0.4 (~ Rin, disk)
DG Tau	~ 260	~ 140 (strong)	~ 32 (Eislöffel & Mundt 1998)	
HL Tau	~ 250	~ 80 (weak)	~ 42±5 (Lay et al. 1997)	
RW Aur	~ 250	~ 100 (very weak)	~46±3 (López-Martin et al. 2003)	

Shibata & Uchida (1986); Kudoh & Shibata (1997)
V (outflow) ~ Keplerian velocity at their launching radius

Discussion: Two V. comp

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

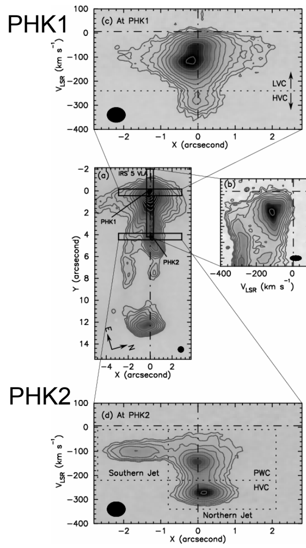
Two V components are clearly distinct in space and velocity

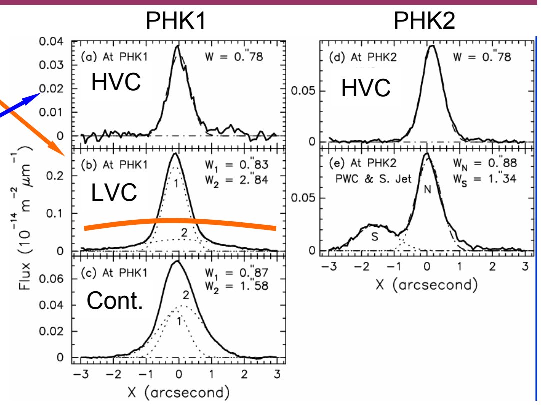
Two outflows Mechanisms? (+ YSOs are X-ray sources.)

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)

Follow Up Observation: L1551 IRS 5





(Pyo et al. 2004, in preparation)

LVC = Widely Opened Fast Wind

Two V components belong to the northern Jet

2002. Nov

Summary

1. [Fe II] λ 1.644 μm emission line observations toward L1551 IRS 5, DG Tau, HL Tau, RW Aur.
2. For All objects we detected two distinct velocity components (HVC and LVC) in space and velocity.
3. We confirmed that LVC of L1551 is spatially widely opened fast wind.
4. Velocity Structure ≠ Onion-like Structure
5. Disks: DG Tau and HL Tau $R_{project}$ ~ 100 AU
6. Redshifted Jet : DG Tau and HL Tau within d < 1”.5
7. Ejection events of knots every 5 years in DG Tau outflows
8. HVC : a well-collimated jet accelerated by the reconnection of dipole stellar magnetic fields anchored to the disk

   LVC : a disk wind with large opening angle driven by magnetocentrifugal force

Thank you