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HIGH ANGULAR RESOLUTION [Fe II] $\lambda 1.644$ μm SPECTROSCOPY OF YSOS WITH SUBARU TELESCOPE

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ABSTRACT

We present results of the velocity-resolved spectroscopy of the [Fe II] $\lambda 1.644$ μm emission toward outflow sources with the Subaru Telescope at the angular resolution of $0.''16 \sim 0.''5$ arcseconds. The observed sources are L1551 IRS 5, DG Tau, HL Tau and RW Aur, which are located in the Taurus-Aurigae Molecular Cloud, one of the closest star forming regions ($0.''1 = 14$ AU). We were able to resolve outflow structure in the vicinity of the sources at a scale of a few tens of AU. The position-velocity diagram of each object shows two velocity components: the high velocity component (HVC: 200 - 400 km s^{-1}) and the low velocity component (LVC: 50 - 150 km s^{-1}), which are clearly distinct in space and velocity. The HVC may be a highly collimated jet presumed from its narrow velocity width and high velocity. The LVC, on the other hand, may be a widely opened disk wind inferred from its broad velocity width and low velocity. The spectrum taken perpendicular to the L1551 IRS 5 outflow at its base shows that the LVC has a spatially wide subcomponent, supporting the above interpretation. We demonstrated that the [Fe II] 1.644 μ spectroscopy is a very powerful tool for the studies of fast jets and winds that directly emanate from star-disk systems.

Key words : ISM: Herbig-Haro objects — ISM: individual(L1551 IRS 5, DG Tauri, HL Tauri, RW Aurigae) — ISM: jets and outflows — stars: formation — stars: pre-main-sequence — techniques: high angular resolution

I. INTRODUCTION

Outflows from young stellar objects (YSOs) are ubiquitous and essential as gravitational collapse in the star formation. Much observational evidence has shown that the outflows are powered by the mass accretion process from disk onto a star (e.g. Hartigan et al. 1995; Edwards, Ray, & Mundt 1993; Cabrit et al. 1990) and play important roles for removing angular momentum from star-disk systems to drive the accretion forward. To make clear understanding outflow launching mechanisms is one of the hottest issues in studying star formation process. To address this issue we need not only high spatial resolution images but also their kinematical information in the vicinity of the central sources. According to theoretical models proposed to date, both magnetic and centrifugal forces play important roles for launching outflows; "*X-wind*"(Shu et al., 2000) or "disk wind" (e.g. Königl & Pudritz 2000; Ferreira 1997). These models predict that the outflow properties are defined within 100 AU from central star, where the outflows are accelerated and collimated. Ground based large telescopes combined with an adaptive optics (AO) systems and space telescopes provide us for high angular resolutions under sub-arcseconds, with which we can resolve a few tens of AU near the outflow driving sources and approach inner region ($\leq$ 100 AU) at the distance to the Taurus-Aurigae Molecular Cloud, d $\sim$ 140 pc ($0.''1 =$ 14 AU). Recently the rotations in the flow, which are predicted by magneto-centrifugal wind models, around the symmetry axis have been detected from several objects at its base by high-angular observations (Coffey et al. 2004; Bacciotti et al. 2002).

We have observed the outflows emanating from young stars with [Fe II] $\lambda 1.644$ μm emission line in $H-$band by using Subaru Telescope. Many Herbig-Haro flows or jets are strong [Fe II] line emitters (e.g. Davis et al. 2003; Nishini et al. 2002; Reipurth et al. 2000). The [Fe II] emission line in near-infrared has the following merits: (1) it is the strongest forbidden line in the $H-$ band, (2) it has small extinction compared to the optical forbidden lines, (3) it traces partially ionized regions of shocked gas. The AO system of the Subaru Telescope was optimized for observing in near-infrared (Takami et al. 2004). The [Fe II] spectroscopy combined with AO thus gives us the best opportunity to probe the regions with large extinction, such as in the vicinity of the young stars, with high angular resolu-

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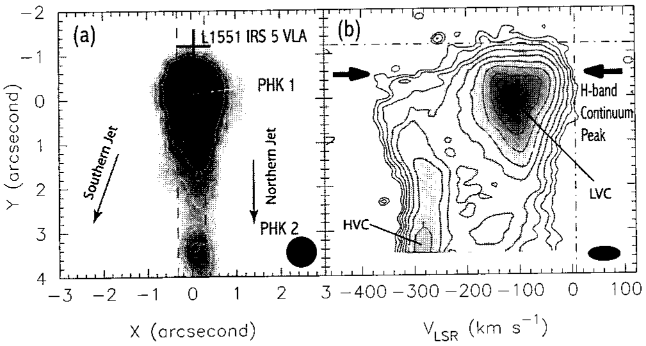

Fig. 1.— (a) Continuum-subtracted [Fe II] λ 1.644 μm image for the L1551 IRS 5 outflows. The big plus mark indicates mid point of the binary system of the VLA sources. The parallel dashed lines indicate the slit aperture of 0.″6 width. The filled circle at the lower right corner shows the seeing size of 0.″6 . (b) Continuum-subtracted position-velocity diagram (PVD) which shows pure [Fe II] emission along the northern jet within the slit indicated left panel *a* (P.A. = 74°). The dash-dotted horizontal line indicate the mid-point of the VLS sources. The dash-dotted vertical line shows the systemic velocity of the L1551 IRS 5 system($V_{\rm LSR}$ = +6.2 km s^{-1}; Momose et al. 1998). The thick horizontal arrows indicate the position of the $H-$band continuum emission peak. The filled elliptical at the lower right corner shows the velocity and the spatial resolutions of 59 km s^{-1} and 0.″3, respectively (Pyo et al. 2002).

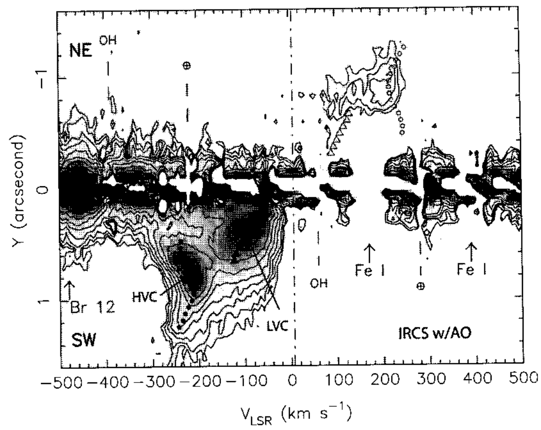

Fig. 2.— Continuum-subtracted PVD in [Fe II] λ1.644μm emission of the DG Tau outflows (Pyo et al. 2003). The P.A. was 222°. The jagged remnant of the stellar continuum at —Y— $\leq$ 0.″23 is affected by the undersampling of the detector. The dash-dotted vertical line shows the systemic velocity at $V_{\rm LSR}$ = +6.4 km s^{-1} (Kitamura, Kawabe, & Saito 1996). The filled circle and triangles trace the peak velocities of the HVC and LVC, respectively. The open circles and triangles are the expected peak velocities for the redshifted outflows drawn symmetric to the filled ones with respect to the systemic velocity and Y =0. The resolutions are 30 km s^{-1} in velocity and 0.″16 in space.

tion. In this contribution, we will introduce the results of the [Fe II] spectroscopic observations with high angular resolution of sub-arcseconds toward L1551 IRS 5, DG Tau, HL Tau, and RW Aur.

II. [Fe II] SPECTROSCOPY WITH HIGH ANGULAR RESOLUTIONS

We observed outflows emanating from young stars with [Fe II] λ1.644 μm emission lines using the Infrared Camera and Spectrograph (IRCS: Kobayashi et al. 2000;Tokunaga et al. 1998). We used the AO system of the Subaru Telescope for observations of DG Tau, HL Tau, and RW Aur. We could not use the AO system for L1551 IRS 5 due to no natural guide star for AO within 30″ from the IRS 5. For former three objects we could use each object itself as the natural guide star for AO. The high angular resolutions of $\leq$ 0.″2 were achieved for DG Tau and RW Aur. The performance of AO correction for HL Tau was not efficient because HL Tau is embedded in $R-$band so it is not a point-like source but a disk-like extended source. As the results we got 0.″5 resolution in space for HL Tau. Figure 1 through 4 show continuum-subtracted position-velocity diagrams (PVDs) of the four objects in [Fe II] λ 1.644 μm emission. The main results of observations are as follows:

(1) We detected two velocity components in all of these four objects: the high velocity components (HVC) at $V = -200 - -400$ km s^{-1} and the low velocity components (LVC) at $V = -50 - -150$ km s^{-1}. These velocities are significantly higher than those of many classical T Tauri stars detected in optical forbidden lines (HVC: $-50 - -150$ km s^{-1}, LVC: $-5 - -20$ km s^{-1}).

(2) We detected redshifted outflows with a gap of ~0.″7 (~ 100 AU) from DG Tau and HL Tau. The gaps indicate optically thick circumstellar disks.

(3) HL Tau and RW Aur show a asymmetry in velocity between the blueshifted and the redshifted outflows, while DG Tau shows symmetrical velocity structure.

(4) We detected strong and broad Br_{12} emission from DG Tau, HL Tau, and RW Aur. While HL Tau shows extended Br_{12} emission feature along the slit/jet, DG Tau and RW Aur show that Br_{12} peaks are coincident with the stellar continuum peaks and the emission is not extended along the slit direction. The extension of the Br_{12} emission from HL Tau is due to scattering by dust particles in the blue lobe (See Close et al. 1997) because the normalized spatial profiles of Br_{12}, LVC, and unidentified emission feature at $V_{\rm LSR}$ = 250 km s^{-1} show similar pattern.

Our results show that the [Fe II] emission, especially with high angular resolution, is a powerful tool to trace fast outflows (winds/jets). Many numerical simulations of magneto-centrifugal wind model show that the terminal velocity of the outflow is order of the Keplerian velocity at the launching radius (e.g. Shibata & Uchida 1986; Kodoh & Shibata 1997a,b; Pesenti et al 2003). Following these results, the HVCs ($|V|$ ~ 200 – 400

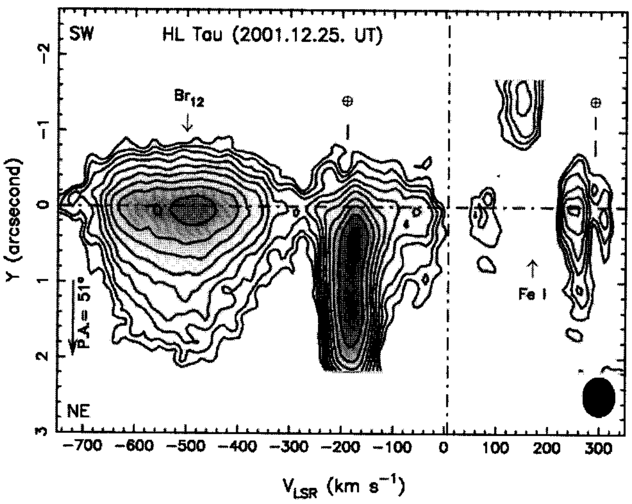

Fig. 3.— Continuum-subtracted PVD in [Fe II] $\lambda1.644\mu$m emission of the HL Tau outflows (Pyo et al. 2004a). The P.A. of slit was 51°. The dash-dotted vertical line indicates the systemic velocity at $V_{\rm LSR} \sim +6.4$ km s^{-1} (Hayashi, Ohashi, & Miyama 1993). The [Fe II] emission line appear $V_{\rm LSR} \geq -280$ km s^{-1}. The strong and extended emission at $V_{\rm LSR} \leq -280$ is Br_{12} emission. The resolutions are 30 km s^{-1} in velocity and $0\farcs5$ in space.

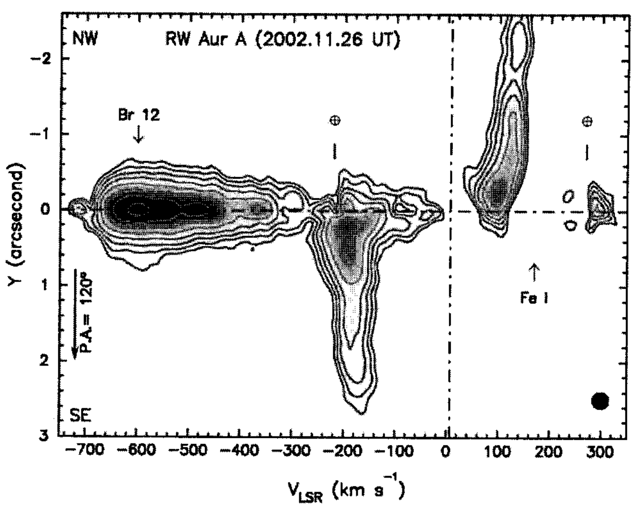

Fig. 4.— Continuum-subtracted PVD in [Fe II] $\lambda1.644\mu$m emission of the RW Aur outflows (Pyo et al. 2004a). The dash-dotted vetical line indicates the systemic velocity at $V_{\rm LSR} = +6.0$ km s^{-1} (Ungerechts & Thaddeus 1987). The P.A. of slit was 120°. The resolutions are 30 km s^{-1} in velocity and $0\farcs2$ in space.

km s^{-1}) may launched from the stellar surface or its vicinity at 0.05 – 0.1 AU and the LVCs($|V| \sim 50-150$ km s^{-1}) may launched from the inner edge of an accreting disk (0.2 – 0.4 AU). The narrow line widths of the HVCs suggest that they may well collimated jets, while the broad line widths of the LVCs indicate that they may widely opened disk winds. Kwan & Tademaru (1988, 1995) already proposed the same arguments with the two velocity components appeared in the optical forbidden emission lines. While we detected the LVC toward RW Aur, the absence of the LVC toward RW Aur was reported by Woitas et al. (2002) and Davis et al.(2003) in optical and near-infrared forbidden emission lines. Woitas et al. (2002) suggested that it could indicate temporal variation on a timescale of a few years.

Recently Pyo et al. (2004b) did follow-up observation for the L1551 IRS 5 outflow with perpendicular slits in order to examine the spatial widths of LVC and HVC. We found that the spatially wide subcomponent in LVC, supporting that the LVC has widely opened wind.

The two distinct outflows, *jets and winds*, may suggest different driving mechanism for each outflow. For example, the HVC is driven by reconnection of the stellar magnetic fields anchored disk inner edge, while the LVC is driven magneto-centrifugal force (e.g. Hayashi, Shibata, & Matsumoto 1996; Goodson, Böhm, & Wing -lee 1999). In order to investigate this hypothesis, we need more information about inter-relations, differences, and temporal variations in physical conditions of these two outflows.

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