High-resolution Near-IR Spectral Mapping with H₂ and [Fe II] Lines of Multiple Outflows around LkH α 234

Heeyoung Oh^{1,2,3} , Tae-Soo Pyo^{4,5} , Bon-Chul Koo¹ , In-Soo Yuk², Kyle F. Kaplan^{3,6} , Yong-Hyun Lee¹ , Kimberly R. Sokal³ , Gregory N. Mace³ , Chan Park², Jae-Joon Lee² , Byeong-Gon Park^{2,7}, Narae Hwang² , Hwihyun Kim⁸ , and Daniel T. Jaffe³

¹ Department of Physics and Astronomy, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea; hyoh@kasi.re.kr

² Korea Astronomy and Space Science Institute, 776 Daedeok-daero, Yuseong-gu, Daejeon 34055, Republic of Korea

³ Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA

⁴ Subaru Telescope, National Astronomical Observatory of Japan, National Institutes of Natural Sciences (NINS), 650 North A'ohoku Place, Hilo, HI 96720, USA

⁵ School of Mathematical and Physical Science, SOKENDAI (The Graduate University for Advanced Studies), Hayama, Kanagawa 240-0193, Japan

⁶ Department of Astronomy/Steward Observatory, The University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

⁷ Korea University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea

⁸ Gemini Observatory, Casilla 603, La Serena, Chile

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Abstract

We present a high-resolution, near-IR spectroscopic study of multiple outflows in the LkH α 234 star formation region using the Immersion GRating INfrared Spectrometer (IGRINS). Spectral mapping over the blueshifted emission of HH 167 allowed us to distinguish at least three separate, spatially overlapped outflows in H₂ and [Fe II] emission. We show that the H₂ emission represents not a single jet but rather complex multiple outflows driven by three known embedded sources: MM1, VLA 2, and VLA 3. There is a redshifted H₂ outflow at a low velocity, $V_{\text{LSR}} < +50 \text{ km s}^{-1}$, with respect to the systemic velocity of $V_{\text{LSR}} = -11.5 \text{ km s}^{-1}$, that coincides with the H₂O masers seen in earlier radio observations 2'' southwest of VLA 2. We found that the previously detected [Fe II] jet with $|V_{\text{LSR}}| > 100 \text{ km s}^{-1}$ driven by VLA 3B is also detected in H₂ emission and confirm that this jet has a position angle of about 240°. Spectra of the redshifted knots at 14''–65'' northeast of LkH α 234 are presented for the first time. These spectra also provide clues to the existence of multiple outflows. We detected high-velocity (50–120 km s^{−1}) H₂ gas in the multiple outflows around LkH α 234. Since these gases move at speeds well over the dissociation velocity (>40 km s^{−1}), the emission must originate from the jet itself rather than H₂ gas in the ambient medium. Also, position–velocity and excitation diagrams indicate that emission from knot C in HH 167 comes from two different phenomena, shocks and photodissociation.

Key words: ISM: individual objects (LkH α 234, HH 167) – ISM: jets and outflows – ISM: molecules – stars: formation – techniques: spectroscopic

1. Introduction

Mass accretion and outflows are essential processes in the formation of stars and planets, as they remove the angular momentum of the infalling material (Hartigan et al. 1995). Massive star formation is not understood well (Zinnecker & Yorke 2007), but massive stars are thought to form in multiple systems and in filamentary structures in molecular clouds (e.g., Pineda et al. 2015). To understand the early stages of the formation of multiple systems, it is important to probe the alignment and orientation of disks and outflows in multiple protostars in testing competing theories on massive star formation, such as “competitive accretion” (Bonnell et al. 1997, 2001) and “stellar collisions and mergers” (Bonnell et al. 1998; Zinnecker & Yorke 2007).

The intermediate-mass star LkH α 234 ($\sim 8.5 M_{\odot}$; Hillenbrand et al. 1992) is located in the NGC 7129 cluster at a distance of $\sim 1.25 \text{ kpc}$ (Shevchenko & Yakubov 1989). LkH α 234 and the surrounding star-forming region are a good place to study the nature of young multiple systems, because this region is one of the most complicated star-forming regions, with multiple outflows from different protostars (e.g., Kato et al. 2011; Oh et al. 2016b). Figures 1 and 2(a) show the positions of the young stellar object (YSO) candidates and axes of the multiple outflows around LkH α 234. The positions of the sources are taken from the radio study by Trinidad et al. (2004).

The first outflow in this region was identified by Edwards & Snell (1983) in $J = 1-0$ ¹²CO, with a redshifted velocity of $\sim 10 \text{ km s}^{-1}$ to the northeast of LkH α 234 with a scale of $\sim 4'$. Herbig-Haro (HH) 167 is an optical jet discovered by Ray et al. (1990); they found high-velocity [S II] emission with a velocity over -100 km s^{-1} extending more than 30'' with a position angle (P.A.) $\sim 252^\circ$. Ray et al. (1990) suggested that this jet could be the counterpart of the red CO lobe, and the prominent [S II] emission within $\sim 15''$ of LkH α 234 is named knots A, B, and C. In the near-IR observation, H₂ emission observed by Schultz et al. (1995) and Cabrit et al. (1997) is consistent with the [S II] knots A, B, and C in HH 167. In larger scale, Eisloffel (2000) detected shocked H₂ emission in the CO outflow region in Edwards & Snell (1983). McGroarty et al. (2004) found that the [S II] emission is spread over 22'' on the sky, indicating a parsec-scale jet.

Radio, millimeter, and mid-IR observations have suggested the presence of YSOs to the immediate northwest of LkH α 234. The radio continuum sources VLA 1, 2, and 3 are detected at $\sim 6''$, $3''$, and $2''$ from LkH α 234 (Trinidad et al. 2004), respectively. The strongest source, VLA 3, is a binary with components of 3A and 3B, and both sources are thought to be emanating radio thermal jets (Trinidad et al. 2004). Another embedded source, FIRS1-MM1, was discovered in millimeter observations by Fuente et al. (2001) $\sim 4''$ northwest of LkH α

Figure 1. IGRINS slit positions for the spectral map of HH 167, observed at the HJST, and of SP1–4, taken with IGRINS on the DCT. Slit sizes are $1''.0$ (W) $\times$ $15''.0$ (L) and $0''.63$ (W) $\times$ $9''.3$ (L) at the HJST and DCT, respectively. (a) The background image is a continuum-subtracted H_2 1–0 S(1) $\lambda 2.122 \mu\text{m}$ narrowband image of the LkH α 234 star-forming region obtained by CFHT. The positive–negative spots in the image are the residuals from the continuum subtraction. The spectral mapping area is shown as a cyan rectangle along the H_2 jet (HH 167). SP1–3 correspond to the redshifted knots northeast of LkH α 234, and SP4 covers part of the “PDR ridge.” (b) Spectral mapping at six different positions from “a” to “f.” Knots A, B, and C of HH 167 are labeled. The crosses mark the sources LkH α 234 (J2000 = 21:43:06.816, +66:06:54.26), VLA 3 (A and B), VLA 2, MM1, and VLA 1 from the southeast to the northwest.

234. A $10 \mu\text{m}$ source (IRS 6) is spatially associated with VLA 3 (Cabrit et al. 1997). Kato et al. (2011) identified mid-IR sources NW 1 and 2 at the positions of IRS 6 and VLA 2, respectively. In Oh et al. (2016b; hereafter Paper I), we presented more details on detections of multiple sources and outflows around LkH α 234.

Trinidad et al. (2004) suggested that VLA 1 is associated with a radio jet on the basis of its elongated morphology. The near-IR H_2 jet has major axis with a P.A. = 227° , being aligned with FIRS1-MM1 (Fuente et al. 2001). Trinidad et al. (2004) and Torrelles et al. (2014) showed that the jet has bipolar kinematics centered on VLA 2, determined from the proper motions of H_2O masers. They suggest that it is possibly related to the optical [S II] outflow based on their similarity in axis, although the origin of the [S II] outflow is not yet clear. The P.A. of the radio thermal jet around VLA 3B is $\sim 230^\circ$, and in Paper I, we found that [Fe II] emission arises from the outflow driven by VLA 3B. None of the outflows seem associated with LkH α 234, implying that this YSO could be in a later evolutionary stage than others (Girart et al. 2016).

With the millimeter observation, Girart et al. (2016) revealed the filamentary dust structure surrounding VLA 1–3 and FIRS1-MM1. They indicated the possibility of a sequential star formation within the filaments based on evolutionary stages. They also detected a compact SiO bipolar outflow with an axis close to the plane of the sky that could be a counterpart of H_2O masers.

Spectral mapping using near-IR, high-resolution spectroscopy is a powerful tool for the analysis of the nature of multiple outflows (e.g., Oh et al. 2016a; Youngblood et al. 2016). The channel maps made from a three-dimensional (3D; x , y , and velocity) data cube provide high-contrast images with ultra-narrowband widths ($\Delta v \sim 10 \text{ km s}^{-1}$). This is better than narrowband imaging filters that have widths corresponding to several thousand km s^{-1} in velocity. There have been several

big H_2 surveys, such as Froebrich et al. (2011) and Walawender et al. (2013), but spectroscopy is the only tool available to measure the amount of shocked material in a definitive way using ratios between multiple emission lines, as well as the kinematic information.

In this work, we extensively study the region around LkH α 234 with a six-pointing spectral map obtained with the Immersion GRating INfrared Spectrometer (IGRINS; Yuk et al. 2010; Park et al. 2014; Mace et al. 2016). Paper I reported an interesting result revealing a new jet driven by VLA 3B with the high-velocity [Fe II] emission, but the narrow spatial coverage and the misalignment of the slit with the jet P.A.s limited the detailed study of the multiple outflow structures. In this paper, we present the result from a spectral map with wider coverage, which allows us to probe the overall kinematics and physics of HH 167 using the mapping with full coverage over the near-IR H_2 jet including knot C. We construct a data cube of H_2 and [Fe II] emission lines, and the channel maps of the data cube allow us to distinguish multiple outflows overlapping spatially but separated in velocity and P.A. We also discuss the orientation of multiple outflows not known before. In addition to the spectral mapping, we present the dynamics and shock properties using the first spectra obtained at the position of the redshifted CO lobe northeast of HH 167 and the surrounding photodissociation region (PDR). Finally, we discuss the role of multiple outflows from a small cluster ridding themselves of their dense envelopes and adding turbulence to the clouds that help to support them in the large scale.

2. Observation and Data Reduction

2.1. NIR Imaging Data

In order to find appropriate slit positions for the observations and to obtain spatial information around LkH α 234, we used an H_2 1–0 S(1) narrowband image of NGC 7129 obtained by the

Figure 2. (a) Positions of the YSOs and axes of multiple outflows around the LkH α 234 region. The background image is a continuum-subtracted H $_2$ 1–0 S(1) narrowband image, and the black contours indicate its intensity in logarithmic scale. The mapping area is marked by a solid white rectangle, and the size is $15'' \times 4''$. The residuals after subtracting LkH α 234 leave a small white area, and the region around LkH α 234 is affected by artificial features due to continuum subtraction. (b)–(c) Monochromatic line images of H $_2$ 1–0 S(1) 2.122 μm and [Fe II] 1.644 μm lines constructed from IGRINS spectral mapping, respectively. The black contours represent the intensity levels of each emission line. The H $_2$ and [Fe II] contours start from the 3σ and 2σ levels and increase with equal intervals in square-root scale to the highest levels of 230σ and 80σ , respectively. The contours of the [Fe II] 1.644 μm emission are superposed on (a) in green. The cyan and green crosses mark the sources LkH α 234 (J2000 = 21:43:06.816, +66:06:54.26), VLA 3A, VLA 3B, VLA 2, MM1, and VLA 1 from the southeast to the northwest. In (a), thin arrows starting from the sources show the outflow axes: blue, red, and white arrows indicate the blueshifted, redshifted, and unknown velocity, respectively. Thick blue and red arrows indicate the axes of the blueshifted optical [S II] jet with P.A. $\sim 252^\circ$ and the redshifted CO lobe, respectively. The black dashed line in (c) is the axis of [Fe II] emission with P.A. = 240° .

Canada–France–Hawaii Telescope (CFHT) IR camera (Starr et al. 2000) at the 3.6 m CFHT. The data were obtained on 2003 November 11 (UT). The CFHT-IR camera used the Rockwell HAWAII $1\text{k} \times 1\text{k}$ HgCdTe array, which provides a field of view of $3'6 \times 3'6$ with a pixel scale of $0''.211 \text{ pixel}^{-1}$. The data were obtained using a narrowband filter (H $_2$ 1–0 S(1), #5339) with the center wavelength and full width at half maximum (FWHM) of $\lambda_c = 2.122 \mu\text{m}$ and $\Delta\lambda = 200 \text{ \AA}$, respectively. We also used the K -continuum filter (#5342) image, with $\lambda_c = 2.260 \mu\text{m}$ and $\Delta\lambda = 600 \text{ \AA}$.

The telescope was dithered to four different directions—northeast, northwest, southeast, and southwest—with respect to the center position (J2000 = 21:43:06, +66:07:09) by $30''$. The total on-source exposure times were 18 s for both H $_2$ and

K -continuum filters, with each single exposure of 2 s. The median seeing during the observation in the K band was $\sim 1''$.

All of the raw data were downloaded from the Canadian Astronomy Data Centre,⁹ and we conducted a data reduction using standard techniques for near-IR imaging data. First, all of the science frames were divided by a normalized flat frame, then they were subtracted by a sky frame that was derived from the median-averaging of all the flat-fielded frames. The astrometry was corrected by comparing the bright, isolated stars in the field with the Two Micron All Sky Survey (2MASS) Point Source Catalog (PSC; Skrutskie et al. 2006).

⁹ <http://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/>

Table 1
Summary of Observations

Object	Date (UT)	Telescope/Instrument	P.A. (deg)	Exposure Time (s)	Slit Size
HH 167 mapping ^a	2015 Aug 6	HJST ^b /IGRINS	225	600 ^c	1''0 × 15''0
HH 167 position "b" ^d	2017 Jun 9	HJST/IGRINS	225	2400	1''0 × 15''0
SP1	2016 Nov 19	DCT ^e /IGRINS	25	300	0''63 × 9''3
SP2	2016 Nov 20	DCT/IGRINS	50	600	0''63 × 9''3
SP3	2016 Nov 20	DCT/IGRINS	44.5	600	0''63 × 9''3
SP4	2016 Nov 19	DCT/IGRINS	90	300	0''63 × 9''3

Notes. The wavelength coverage and resolving power of IGRINS are the same on HJST and DCT: 1.49–2.46 μm and $R \equiv \lambda/\Delta\lambda \sim 45,000$.

^a The spectral mapping on HH 167 with a total of six slit positions, a–f.

^b The 2.7 m Harlan J. Smith Telescope at the McDonald Observatory.

^c Total integration time at each slit position of the spectral map.

^d Deep pointing on slit position "b" in HH 167.

^e The 4.3 m Discovery Channel Telescope at the Lowell Observatory.

All of the preprocessed frames were then combined into a final image.

2.2. IGRINS Observation

We used data from IGRINS at two different telescopes: the 2.7 m Harlan J. Smith Telescope (HJST) at the McDonald Observatory and the 4.3 m Discovery Channel Telescope (DCT) at Lowell Observatory. IGRINS covers the whole wavelength range of the infrared H and K bands (1.49–2.46 μm) simultaneously, with a spectral resolving power $R \equiv \lambda/\Delta\lambda \sim 45,000$. The wavelength coverage and the resolving power of IGRINS are the same on both telescopes. The resolving power corresponds to a velocity resolution (Δv) of 7 km s^{−1}, with ~ 3.5 pixel sampling. Table 1 presents the summary of the IGRINS observations, and the details of the observations using HJST and DCT are described below.

2.2.1. Spectral Mapping with HJST

On 2015 August 6 (UT), we obtained a spectral map toward the H₂ jet (HH 167) southwest of LkH α 234 using HJST. The slit size on the sky, which changes depending on the telescope, was 1''0 × 15''0 at HJST. The pixel scale was 0''24–0''29 pixel^{−1} along the slit, and the value was larger in higher orders. Autoguiding was performed during each exposure with a K -band slit-viewing camera (pixel scale = 0''12 pixel^{−1}). The guiding uncertainty was smaller than 0''4, on average, and the FWHM of stars in the K -band slit-viewing camera was $\sim 0''9$, which establishes the angular resolution of the spectral map.

The spectral map was completed by performing six adjacent observations, offset by 0''7 steps perpendicular to the slit length. This map covers an $\sim 15'' \times 4''3$ area including knots A, B, and C of HH 167 jet. Figure 1 shows the slit positions on the sky. The slit P.A. was 225°. The total on-source integration time was 600 s at each slit position. The observing sequence for this program included object–sky–object observations for each slit position. The sky frame was obtained at a position 180'' east of the on-source position. We also observed an A0V-type star (HR 8598; $K = 6.32$ mag) for telluric correction, and Th-Ar and halogen lamp frames were taken for wavelength calibration and flat-fielding, respectively.

On 2017 June 9 (UT), we acquired additional spectra in order to probe the properties of high-velocity H₂ emission with the line ratios. For the high-excitation lines, higher signal-to-noise ratio

(S/N) data are required than what was obtained with the original mapping. A deep pointing at the single position "b" (see Figure 1), where we found the strongest high-velocity H₂ emission, was conducted. The telescope and instrument settings and slit P.A. were kept consistent with those used in previous observations in 2015. The total on-source exposure time for this single pointing was 2400 s, and an A0V-type star (HD 191940; $K = 6.60$ mag) was observed as a telluric star.

2.2.2. Single Slit Positions with DCT

In addition to the spectral mapping over HH 167, we obtained spectra at additional slit positions of interest. The data were obtained on 2016 November 19–20 (UT) while IGRINS was installed at the DCT. On the DCT, the slit size was 0''63 × 9''3. The pixel scale along the slit was therefore reduced by a factor of ~ 0.63 . The wavelength coverage and spectral resolving power of IGRINS remained the same. We selected four separate slit positions on the H₂ emission: three positions to the northeast of LkH α 234, which are spatially coincident with the redshifted CO outflow (Edwards & Snell 1983; Eisloffel 2000), and one position on the "PDR ridge" (Morris et al. 2004) to the south of LkH α 234. The slit positions (SP1–4) are shown in Figure 1. The slit P.A.s were 25°, 50°, 44.5°, and 90° for SP1–4, respectively. An A0V-type telluric star (HR 8598; $K = 6.32$ mag) was also observed. The total integration time was 300 s for SP1 and SP4 and 600 s for SP2 and SP3, respectively.

2.2.3. Data Reduction

Basic data reduction was done using the IGRINS Pipeline Package v2.2.0-alpha.3¹⁰ (PLP; Lee et al. 2017). The PLP performs sky subtraction, flat-fielding, bad-pixel correction, aperture extraction, and wavelength calibration. After running the PLP, additional processes are conducted using Plotspec¹¹ (Kaplan et al. 2017), which has been developed for the processing of two-dimensional (2D) spectra from IGRINS data. Plotspec provides continuous 2D spectra of all IGRINS H - and K -band orders, removal of stellar photospheric absorption lines from the standard star, telluric correction, and relative flux calibration. The continuum is subtracted using pixel values

¹⁰ The IGRINS Pipeline Package is downloadable at <https://github.com/igrins/plp>. (doi:10.5281/zenodo.18579).

¹¹ <https://github.com/kfkaplan/plotspec>

Table 2
Detected H₂ Lines from SP1–4^a

Transition	λ_{vac}	Flux ^b			
		SP1	SP2	SP3	SP4
4–2 O(3)	1.509865	...	...	...	25.69 ± 0.98
5–3 Q(4)	1.515792	...	...	...	7.69 ± 0.92
5–3 O(2)	1.560730	...	...	...	12.70 ± 0.69
4–2 O(4)	1.563516	...	...	...	14.97 ± 0.62
6–4 Q(1)	1.601535	...	...	...	20.57 ± 0.60
5–3 O(3)	1.613536	...	...	...	21.96 ± 0.73
6–4 Q(3)	1.616211	...	...	...	10.20 ± 0.54
7–5 S(1)	1.620530	...	...	...	13.23 ± 0.58
4–2 O(5)	1.622292	...	...	...	12.35 ± 0.71
5–3 O(4)	1.671821	...	...	...	12.38 ± 0.68
6–4 O(2)	1.675019	...	...	...	12.37 ± 0.54
1–0 S(9)	1.687721	...	...	...	3.99 ± 0.65
7–5 Q(1)	1.728779	...	...	...	12.42 ± 0.76
6–4 O(3)	1.732637	...	...	...	18.52 ± 1.09
5–3 O(5)	1.735888	...	...	...	8.63 ± 0.68
1–0 S(7)	1.748035	...	...	...	1.99 ± 1.25
1–0 S(6)	1.787946	...	...	...	0.50 ± 0.83
1–0 S(3)	1.957556	81.30 ± 1.00	...	73.47 ± 3.39	69.22 ± 1.28
1–0 S(2)	2.033756	32.32 ± 0.39	32.13 ± 1.04	31.86 ± 0.77	49.41 ± 0.56
8–6 O(3)	2.041816	...	...	...	8.76 ± 0.62
2–1 S(3)	2.073510	...	...	...	29.19 ± 1.87
8–6 O(4)	2.121570	...	...	...	4.85 ± 0.43
1–0 S(1)	2.121831	100.00 ± 0.39	100.00 ± 0.80	100.00 ± 0.65	100.00 ± 0.55
2–1 S(2)	2.154225	4.51 ± 0.34	3.57 ± 0.96	3.96 ± 0.67	23.01 ± 0.48
9–7 O(2)	2.172704	...	...	...	4.15 ± 0.53
3–2 S(3)	2.201397	3.90 ± 0.36	...	3.75 ± 0.73	12.42 ± 0.54
8–6 O(5)	2.210741	...	...	...	3.88 ± 0.90
1–0 S(0)	2.223299	26.40 ± 0.38	21.25 ± 1.00	22.64 ± 0.74	62.32 ± 0.60
2–1 S(1)	2.247721	12.96 ± 0.42	8.90 ± 1.04	13.42 ± 0.80	46.61 ± 0.67
4–3 S(3)	2.344479	...	...	...	5.01 ± 0.67
1–0 Q(1)	2.406594	112.94 ± 0.66	65.14 ± 5.38	98.34 ± 1.42	136.73 ± 0.96
1–0 Q(2)	2.413436	36.00 ± 0.75	...	30.43 ± 1.58	71.53 ± 1.08
1–0 Q(3)	2.423731	114.98 ± 0.81	86.02 ± 5.31	98.49 ± 2.06	76.71 ± 1.08
1–0 Q(4)	2.437491	33.59 ± 0.71	23.80 ± 1.83	26.20 ± 1.58	31.83 ± 1.08

Notes.

^a SP1–4 in Figure 1.

^b Reddening is corrected with $A_V = 21, 16,$ and 7 for SP1, 2, and 3, respectively. In SP4, reddening is not corrected because $A_V \sim 0$. Fluxes are normalized to the 1–0 S(1) line, which is set to 100.

obtained by a robust-median filter running along the wavelength direction. With the Plotspec code, we then constructed a 3D data cube from the spectral mapping data.

3. Results

We detected 14 H₂ and 5 [Fe II] lines from knots A, B, and C of HH 167 in the 1.49–2.46 μm range covered by IGRINS. The lists of detected lines are reported in Tables 1 and 2 of Paper I. From the redshifted knots SP1–3, we detected 8–11 H₂ lines, and we did not detect any [Fe II] emission, probably due to the large extinction in the H band. In SP4, which covers the PDR ridge (see Figure 1), high-excitation lines of H₂ with v (the upper vibrational level of H₂) ≤ 9 are detected, and [Fe II] emission was found. Table 2 lists the detected H₂ lines from SP1–4. Our analysis of the data cube constructed from the spectral map utilizes channel maps and position–velocity diagrams (PVDs). The strongest H₂ 1–0 S(1) 2.122 μm and [Fe II] $a^4D_{7/2} - a^4F_{9/2}$ 1.644 μm lines are used to study the kinematics and origin of the multiple outflows. We presented the detailed physics from the line ratios between different

[Fe II] lines in Paper I by estimating an electron density of $\sim 1.1 \times 10^4 \text{ cm}^{-3}$, which is similar to or slightly smaller than the values in outflows from T Tauri stars or Class 0–I sources.

3.1. Spectral Mapping of the HH 167 Outflow

3.1.1. Monochromatic Images

Figure 2(a) shows a close view of the narrowband H₂ 1–0 S(1) emission image taken with CFHT-IR/CFHT shown in Figure 1. Knot A shows complicated structure with multiple peaks in intensity. It consists of two bright peaks at the eastern and western parts of knot A and another two minor peaks at the southern and northern parts. We note the possible contamination in H₂ emission close to the sources due to the residuals after the subtraction of continuum emission from LkH α 234. In Section 3.1.2, we will show that these different peaks in knot A trace different velocities in the channel maps. The shape of knot B is elongated along the northeast–southwest direction with a size of $4''5$ in length, showing a good agreement with the major axis of P.A. $\sim 225^\circ$. Knot C is located at the southwestern tip of the stream and shows clumpy structure.

Figure 3. Channel maps of the H_2 1–0 S(1) 2.122 μm line (top) and $[\text{Fe II}]$ 1.644 μm line (bottom). The intensity is integrated over successive 20 km s^{-1} intervals. The radial velocity increases from left to right, and the central velocity (V_{LSR}) in km s^{-1} is marked at the bottom of each channel map. The H_2 and $[\text{Fe II}]$ contours start from the 5σ and 3σ levels and increase with equal intervals in square-root scale to the highest levels of 37σ and 10σ , respectively. The slit P.A. is 225° . Slit positions “a” to “f” are located from right to left in each channel map (see Figure 1 inset in the top right corner). The peaks “A1’,” “A2’,” and “B” identified in Paper I are marked. Peak “C,” corresponding to knot C, is also marked. Dotted and dashed lines and circles in different colors indicate the axes and peak positions of the identified outflows: dotted magenta lines, VLA 3B outflow; dashed green lines, FIRS1-MM1 outflow; black ellipses, redshifted outflow from VLA 2; blue circles, an additional possible outflow from VLA 2 or 3.

The spectral mapping area is overlaid on Figure 2(a) with a white rectangle. Figures 2(b) and (c) show images of the H_2 1–0 S(1) 2.122 μm and $[\text{Fe II}]$ 1.644 μm emission lines integrated over a velocity range of $-180 \text{ km s}^{-1} < V_{\text{LSR}} < +60 \text{ km s}^{-1}$. In H_2 1–0 S(1) emission, the integrated-intensity distribution matches well with the H_2 narrowband image, showing the substructures of knots A, B, and C. The P.A. of the H_2 emission is $\sim 225^\circ$, as shown in the previous imaging study by Cabrit et al. (1997). The peak intensity is highest in knot A, and it is weaker in knots B and C by fractions of 0.25 and 0.16, respectively.

The $[\text{Fe II}]$ emission shown in Figure 2(c) is very different from H_2 in morphology. The axis of $[\text{Fe II}]$ emission is $\sim 240^\circ$ and is well aligned with the position of the radio continuum source VLA 3. This result supports the idea presented in Paper I, which argued that this $[\text{Fe II}]$ emission arises from the outflow driven by VLA 3B. The details of this emission will be discussed more in Section 4 in combination with the results from channel maps. The $[\text{Fe II}]$ emission shows a single peak in knot A, and its peak position is consistent with a small peak in H_2 emission in the southern part of knot A. The $[\text{Fe II}]$ emission peak in knot A is located $1''.5$ south of the H_2 peak in Figure 2(b). The peak $[\text{Fe II}]$ intensity of knot C is ~ 0.34 times the knot A intensity, although knots A and C are not fully covered in the slit-scan area. Emission from knot B is about 10 times weaker than that from knot A. In knot C, the $[\text{Fe II}]$ emission peaks $1''.5$ west of the H_2 peak emission. We note that extinction can cause the differences in morphology of $[\text{Fe II}]$ and H_2 emission, as extinction in the H band is larger than that in the K band with a ratio of $A_H/A_K \sim 1.56$ (Rieke & Lebofsky 1985). The measurement of the extinction is described in Section 3.4.1 in detail.

3.1.2. Channel Maps

Figure 3 shows channel maps of the H_2 2.122 μm 1–0 S(1) and $[\text{Fe II}]$ $\lambda 1.644 \mu\text{m}$ emission lines. The channel maps are

constructed with 20 km s^{-1} velocity intervals in the range $-180 \text{ km s}^{-1} < V_{\text{LSR}} < +60 \text{ km s}^{-1}$. We take the systemic velocity as $V_{\text{LSR}} \sim -11.5 \text{ km s}^{-1}$, which is the central velocity of the molecular emission (e.g., SO_2) from radio continuum source VLA 2 taken from Girart et al. (2016). The channel maps show that H_2 and $[\text{Fe II}]$ emission are different not only in position but also in velocity. The H_2 is dominant in a lower velocity when compared to $[\text{Fe II}]$ emission, but it shows more complex structure with multiple velocity components detected over a very wide velocity range.

In the channel maps of -30 , $+10$, and -10 km s^{-1} , we mark the peaks corresponding to “A1’,” “A2’,” and “B” identified in Paper I. We also mark a new peak, “C,” which arises from knot C. At the position of knot A, H_2 is detected in all velocity channels, including both blueshifted and redshifted components. The two strong velocity peaks A1’ and A2’ show positional agreement with two strong intensity peaks in knot A shown in Figure 2(a). Peak A1’ shows the highest intensity level among the area of spectral mapping. In the channel centered on -10 km s^{-1} , knot A shows double peaks with somewhat “transitional” morphology between A1’ and A2’. The emission from knot B is detected in the range of $-60 \text{ km s}^{-1} < V_{\text{LSR}} < +20 \text{ km s}^{-1}$, with a peak value near the systemic velocity of -11.5 km s^{-1} . Knot C is more prominent at higher velocity than both knot A and knot B and is centered on the -70 km s^{-1} channel map.

Channel maps of the $[\text{Fe II}]$ line show that knot A has the strongest emission at -110 km s^{-1} . The peak of $[\text{Fe II}]$ emission from knot B is not clear but is most prominent in the channel of -130 km s^{-1} . The $[\text{Fe II}]$ emission from knot C peaks at a velocity higher than that of knots A and B, similar to the H_2 emission. The $[\text{Fe II}]$ peaks at much higher velocity than H_2 in all of the knots.

In the channel maps, the dotted lines and circles in different colors mark the axes and positions of the features that might arise from the different outflows. The magenta lines in the maps of H_2 and $[\text{Fe II}]$ mark the P.A. of 240° . These lines correspond to the black dashed line in Figure 2(c), which is aligned well with the radio continuum VLA 3. This axis is traced in all three knots in both H_2 and $[\text{Fe II}]$ in a wide velocity range of $-180 \text{ km s}^{-1} < V_{\text{LSR}} < +60 \text{ km s}^{-1}$. The emission along this axis is brighter in $[\text{Fe II}]$ than H_2 , while weak H_2 traces the whole $[\text{Fe II}]$ emission along the magenta line, as clearly seen at $V_{\text{LSR}} = -130 \text{ km s}^{-1}$. Along this axis, the peak velocities of both H_2 and $[\text{Fe II}]$ emission are very similar in all knots, as shown in channels of -110 , -130 , and -150 km s^{-1} for knots A, B, and C, respectively. The green vertical line shows the axis of P.A. = 225° , which is equal to the major axis of H_2 emission in Figure 2(a). Along this axis, the H_2 emission is again detected in all three knots in a wide velocity range of $-100 \text{ km s}^{-1} < V_{\text{LSR}} < +20 \text{ km s}^{-1}$. Very weak $[\text{Fe II}]$ emission from knots B and C traces this axis but is marginally detected with $\sim 1\sigma$ level (see panels (b) and (c) in Figure 4). Black ellipses in the channel maps of $+10$ and $+30 \text{ km s}^{-1}$ mark the redshifted component in the knot A position. Additionally, blue circles in channel maps at -50 and -30 km s^{-1} indicate emission from peak A1'.

3.1.3. Position Velocity Diagrams

The PVDs provide more precise information on velocity and position than the channel maps for a given emission component, because a channel map is produced by collapsing the data cube along the velocity axis, losing detailed information otherwise attainable from a PVD. Figures 4–5 show the PVDs of the H_2 2.122 μm 1–0 S(1) and $[\text{Fe II}]$ 1.644 μm emission lines. In both figures, white contours represent the H_2 emission, and the $[\text{Fe II}]$ emission is shown as the color intensity map. The slit P.A. is 225° in all PVDs we show in this study. In Paper I, the slit P.A. was 256° . The dash-dotted vertical lines mark the systemic velocity at $V_{\text{LSR}} = -11.5 \text{ km s}^{-1}$. We described the PVDs covering knots A and B in HH 167 in Paper I in detail. The overall results for those two knots are similar to those of Paper I. In Figure 4, the PVDs from slit positions “a”–“f” marked in Figure 1 are shown. In panels (b)–(d), we mark the peaks B, A2', and A1', respectively. Figure 4(c) shows that the peak velocity of the redshifted emission of peak A2' seen in channel maps (black ellipses in Figure 3) is $V_{\text{LSR}} \sim -5 \text{ km s}^{-1}$ ($V_{\text{sys}} = -11.5 \text{ km s}^{-1}$) at $Y = -2''$. In panel (b), knot B shows peak velocity at $Y = -6''$ with $V_{\text{LSR}} \sim -15 \text{ km s}^{-1}$, as in Paper I. Knot C in H_2 shows peak velocity at $V_{\text{LSR}} = -81 \text{ km s}^{-1}$ and $Y = -10''.5$. At the position of knot A, $[\text{Fe II}]$ emission peaks at -113 km s^{-1} in slit position “e.” Knot C in $[\text{Fe II}]$ shows the highest velocity of HH 167 with $V_{\text{LSR}} \sim -150 \text{ km s}^{-1}$.

Figure 5 shows the integrated PVD of all slit positions in the spectral mapping (positions “a”–“f” in Figure 1). Dotted and dashed lines indicate two different trends traced by low- and high-velocity components in H_2 emission. Along the dotted line, the high-velocity $[\text{Fe II}]$ emission is well traced by the H_2 line in both position and velocity. In contrast, very weak $[\text{Fe II}]$ emission is detected along the dashed line. The gradients in radial velocity ($\delta v/\delta l$) in the dotted and dashed lines are ~ 3 and $5 \text{ km s}^{-1} \text{ arcsec}^{-1}$, respectively.

Figure 4. PVDs of H_2 1–0 S(1) 2.122 μm (white contours) and $[\text{Fe II}]$ 1.644 μm (color intensity map) emission. Panels a–f correspond to slit positions “a”–“f” in Figure 1. The slit position angle is 225° in all panels, with northeast up. The contour starts from a 3σ level, and it increases with equal intervals in a logarithmic scale. The continuum emission is subtracted. The vertical dash-dotted line indicates the systemic velocity ($V_{\text{LSR}} = -11.5 \text{ km s}^{-1}$; Girart et al. 2016). Peaks “B” and “C” are marked in (b), and “A2” and “A1” are marked in (c) and (d), respectively. Solid rectangles in (b) and (c) mark the regions used to calculate the excitation diagrams in Figures 9(d)–(g).

Figure 5. Integrated PVDs of H_2 1–0 S(1) $2.122\ \mu\text{m}$ (white contours) and $[\text{Fe II}]$ $1.644\ \mu\text{m}$ (color intensity map) emission. Northeast is up and southwest is down in the diagrams (P.A. = 225°). The PVDs at slit positions “a”–“f” are summed to show the overall kinematic information in the spectral mapping area. The contour starts from a 3σ level, and it increases with equal intervals in a logarithmic scale. The background continuum emission is subtracted. Dotted and dashed lines indicate the velocity gradients of different outflows associated with VLA 3B and FIRS1-MM1, respectively. The vertical dash-dotted line marks the systemic velocity ($V_{\text{LSR}} = -11.5\ \text{km s}^{-1}$).

3.2. Redshifted Knots to the Northeast of LkH α 234

We have obtained the first near-IR spectra of the redshifted knots to the northeast of LkH α 234, which are the counterparts of the blueshifted HH 167 jet. The location of the knots corresponds to the position of the redshifted CO lobe shown in Edwards & Snell (1983). We observed three selected positions, SP1–3, shown in Figure 1. Figure 6 shows the PVDs of H_2 1–0 S(1) emission lines from the three positions. SP1 is located $\sim 65''$ northeast of LkH α 234. The peak velocity at this position is $\sim -5\ \text{km s}^{-1}$, which is close to the systemic velocity ($V_{\text{sys}} = -11.5\ \text{km s}^{-1}$) but $\sim 5\ \text{km s}^{-1}$ redshifted. As shown in Figure 1, the distances from LkH α 234 to SP2 and SP3 are $14''$ – $16''$ at a P.A. difference of about 20° . The PVDs from SP2 and SP3 show that they are also different in velocity. SP2 shows multiple peaks in velocity, with the lower-velocity component peaking at $V_{\text{LSR}} \sim +12\ \text{km s}^{-1}$, and the high-velocity component shows double peaks at $+72$ and $+102\ \text{km s}^{-1}$. The intensity of the high-velocity peaks is 5 times higher than that of the low-velocity peak. This double peak at high velocity and separated by 20 – $30\ \text{km s}^{-1}$ is very typical of an unresolved bow shock internal to the fast collimated wind (e.g., L1448, Davis & Smith 1996; DR 21, Smith et al. 2014). Imaging studies of HH objects with high spatial resolution show that they consist of a chain of small bow-like knots (e.g., Hartigan et al. 2001; Reipurth et al. 2002). Considering the $1.25\ \text{kpc}$ distance of the LkH α 234 system, the double peak may represent the superposition of multiple bows. The peak velocity at SP3 is similar to that of SP1 but shows slightly higher velocity with $V_{\text{LSR}} \sim -2\ \text{km s}^{-1}$.

3.3. Surrounding PDR

In addition to the redshifted knots, we observed a part of the PDR ridge to the southwest of LkH α 234 (SP4). The slit position is $\sim 43''$ south of LkH α 234, as shown in Figure 1. Morris et al. (2004) reported that the UV field strength at this H_2 ridge is comparable to that of the reflection nebula NGC 7023 from the polycyclic aromatic hydrocarbon band intensities using the *Spitzer* Infrared Spectrograph (IRS; Houck et al. 2004). Figure 7 shows the PVD and line profile of the H_2 1–0 S(1) line obtained from the PDR ridge. The velocity width in the line profile corresponds to the spectral resolution

Figure 6. PVDs of H_2 1–0 S(1) $2.122\ \mu\text{m}$ of redshifted knots northeast of LkH α 234. The top, middle, and bottom panels correspond to SP1, SP2, and SP3 in Figure 1 with a slit P.A. of 25° , 50° , and 44.5° , respectively. The contour starts from a 3σ level, and it increases with equal intervals in a logarithmic scale. Solid rectangles mark the regions used to derive the excitation diagrams in Figures 9(a)–(c).

element ($\sim 7\ \text{km s}^{-1}$) at a systemic velocity of $-11.5\ \text{km s}^{-1}$. The widths of all detected lines are narrow and consistent with the typical value from a normal PDR, which is $V_{\text{FWHM}} < 5\ \text{km s}^{-1}$ (e.g., Hogerheijde et al. 1995).

3.4. H_2 Line Ratios

3.4.1. Extinction Measurement

We estimate the extinction around LkH α 234 by employing the line ratios of H_2 lines that arise from the same upper level. In this study, the pair of $v = 1$ –0: Q(3) $2.424\ \mu\text{m}$ /S(1) $2.122\ \mu\text{m}$ is used because these lines are not impacted by telluric absorption or OH emission. Using the transition probabilities of two lines taken from Turner et al. (1977), the intrinsic intensity ratio of the Q(3)/S(1) lines is given as ~ 0.7 . For the calculation of the visual extinction (A_V) using given predicted (R_p) and observed (R_o) line ratios, we adopted the equation from Petersen & Gammelgaard (1996):

$$A_V = \frac{2.5 \log (R_o/R_p)}{A_{\lambda_2}/A_V - A_{\lambda_1}/A_V} \text{ mag.} \quad (1)$$

In the equation above, λ_1 and λ_2 are the wavelengths of the Q(3) and S(1) lines, respectively. We use the extinction law

Figure 7. PVD (top) and line profile (bottom) of H₂ 1–0 S(1) 2.122 μ m obtained at SP4 (the PDR ridge). The slit position is shown in Figure 1. Here, V_{FWHM} is ~ 7 km s^{−1} at the systemic velocity, which corresponds to the resolution limit of the instrument. The weak component detected at $V_{\text{LSR}} = -45$ km s^{−1} is emission from the H₂ 8–6 O(4) transition and also arises in the PDR. The region within the solid rectangle is used to calculate an excitation diagram in Figure 9(h). East is up and south is down in the diagram.

$A_{\lambda} = A_V(0.55 \mu\text{m}/\lambda)^{1.6}$ (Rieke & Lebofsky 1985) to calculate the A_{λ}/A_V . The uncertainties of the line fluxes are propagated from the pixel variance given by the PLP. The channel maps of the 1–0 Q(3) and S(1) lines are smoothed with a Gaussian mask of 2×2 pixels to reduce the impact of noise in the calculation.

For the spectral mapping area, Figure 8 shows the A_V in the form of channel maps over a velocity range of $-160 \text{ km s}^{-1} < V_{\text{LSR}} < +40 \text{ km s}^{-1}$. We also plot the S/N of the Q(3)/S(1) line ratio and the uncertainties in the A_V measurement for each channel map in Figure 8. In the extinction plot, we excluded pixels with $\text{S/N} < 3$ in the calculated line ratio. Within the plotted regions, the uncertainties in the A_V measurements are in a large range of 0–15 mag. The A_V varies largely in position and velocity in the range of $0 < A_V < 40$, which corresponds to $A_K = 0$ –4.6. The extinctions in the blueshifted emission with high velocity in the range of $-160 \text{ km s}^{-1} < V_{\text{LSR}} < -80 \text{ km s}^{-1}$ are higher than that of lower velocity ($-70 \text{ km s}^{-1} < V_{\text{LSR}} < +40 \text{ km s}^{-1}$), showing A_V higher than 35 in some regions. We note, however, that most of the high-extinction pixels shown in yellow in Figure 8 are on the boundary of unplotted regions, and their uncertainties are relatively higher. We suspect that the calculated extinction values in these regions are less reliable. The extinction is relatively small ($0 < A_V < 10$) in the low-velocity range. At the left side of the figure, we also show A_V in the velocity-integrated image. Similar to those in low velocity, the extinction in the integrated map varies between 0 and 10, except for the yellow part with low reliability. This is an expected result because most of the flux in the integrated map is from low velocity. We also estimate the extinction for SP1–4 using the same H₂ line ratios. Extinction at the redshifted knot SP1 is highest ($A_V \sim 21$). SP2 and SP3 show smaller values (~ 7 and 16, respectively). At SP4, the PDR south of LkH α 234, the measured A_V is close to zero.

3.4.2. H₂ Line Properties

The line ratios between various H₂ emission lines allow us to probe the gas properties (Black & van Dishoeck 1987; Smith 1995). We measure the line ratios from eight different positions around LkH α 234, including redshifted and blueshifted knots and ambient PDR. The H₂ excitation diagrams in Figure 9 show the column density ($N(v, J)/g(v, J)$, where $g(v, J)$ is the statistical weight for the vibrational and rotational levels v and J) plotted against the excitation temperature (E). The different colors and shapes of the symbols represent different vibrational levels and the ortho/para forms of the H₂ lines, respectively. The H₂ narrowband image in Figure 1 shows the slit positions from which the line ratios are measured for deriving the excitation diagrams. Also, selected position–velocity ranges are marked by boxes on the PVDs in Figures 4, 6, and 7. Figures 9(a)–(c) (SP1–3) correspond to the redshifted knots to the northeast of HH 167, and Figures 9(d)–(e) correspond to knots A and B, respectively. Figures 9(f) and (g) are derived from the same position of knot C, but they represent different velocity components: the high-velocity shock component ($-100 \text{ km s}^{-1} < V_{\text{LSR}} < -50 \text{ km s}^{-1}$) and the PDR close to the systemic velocity ($-23 \text{ km s}^{-1} < V_{\text{LSR}} < +2 \text{ km s}^{-1}$), respectively. Figure 9(h) (SP4) is part of the PDR ridge 43" south of LkH α 234. The reddening is corrected with A_{λ} at each position with the values indicated in Section 3.4.1. The A_K value is shown in each panel in Figure 9.

We exclude the lines affected by OH sky emission or telluric absorptions and with S/N below 2. There is an observational factor affecting the number of data points in the different positions. Fewer H₂ emission lines with $v = 1$ are measured in (a)–(c) than in (d)–(e) because the extinction is stronger in redshifted knots ($A_K = 1.9$ –2.4) than in a blueshifted region ($A_K = 0.1$ –0.8). In the *H* band, where the effects due to extinction are much higher, we miss the H₂ lines from a higher rotational level (J) in $v = 1$. In (f), there are fewer points despite weaker extinction ($A_K \sim 0.1$) in knot C. The reasons for this are the lower S/N in knot C than in knots A and B (see also Section 3.1.1) and contamination by OH and telluric lines in the high-velocity range of knot C.

The outflow regions (Figures 9(a)–(f)) and ambient PDR (Figures 9(g)–(h)) show clear differences in the shapes of excitation diagrams and the transition levels of detected emission lines. We detect lines with $v = 1$ –3 in the outflow regions and $v = 1$ –9 in the PDRs. Observed H₂ populations follow signatures of typical shocked regions and PDRs, where the shocked H₂ emission represents a thermalized population being aligned on a single line in the excitation diagram (e.g., Beckwith et al. 1978), while we expect multiple vibrational temperatures from PDRs (e.g., Kaplan et al. 2017). The H₂ populations are nonthermal due to UV fluorescence in the PDR, so we are able to distinguish it from the thermal level populations found in shocked H₂. We suspect that the emission from outflow mostly arises from the cooling of shocked gas. In Section 4, we discuss more on excitation diagrams in comparison with various shock models and previous observations of Orion KL.

4. Discussion

4.1. Multiple Outflows and Sources

In Section 3.1.2, we showed four different emission features traced by lines and circles in Figure 3. The origin of these

Figure 8. Visual extinctions (A_V) of channel maps derived from a line ratio of $H_2 v = 1-0$: Q(3)/S(1) (top), the S/N of the line ratio (middle), and the uncertainty in the A_V measurement (bottom). The P.A. is 225° , with northeast at the top. The central velocity is marked at the bottom of each channel map. The panels on the leftmost side show the maps with integrated velocity in $-160 \text{ km s}^{-1} < V_{\text{LSR}} < +40 \text{ km s}^{-1}$. Pixels with $S/N < 3$ in the line ratio are excluded in the A_V plot. The channel maps of the Q(3) and S(1) lines are smoothed with a Gaussian mask of 2×2 pixels before the calculation of the extinction.

emission features can be interpreted as either a single outflow, even if they are not aligned perfectly with each other, or multiple outflows originating from multiple sources. As a basis for the single-outflow case, there are examples of flows with kinks and curves in them and poorly collimated jets (e.g., HH jets in NGC 1333, Bally & Reipurth 2001; HL/XZ τ jet, Movsessian et al. 2007; and L1660, Davis et al. 1997). It is often the case that a single outflow produces two very different phenomena: an internal shock in the fast jet that shows up at high-velocity emission and a shock of the swept-up material into the ambient cloud that appears close to the ambient cloud velocity (Pyo et al. 2003; Bally et al. 2007). Also, the positions and velocities of H_2 and [Fe II] emission could be different when they arise from a single outflow, since they originate from different shock regions (Pyo et al. 2002; Davis et al. 2003).

However, we prefer the interpretation with multiple outflows through the identification of at least three separate outflows. The channel maps in Figure 3 show that different kinematic features have different velocity-space vectors in a 3D geometric space, and there are multiple YSO candidates within $5''$ of the bases of the different outflow vectors. In addition, submillimeter and radio observations have reported on multiple outflows in this area (Trinidad et al. 2004; Girart et al. 2016). We argue that the multiple outflows originate from VLA 3B, MM1, and VLA 2. Below, we describe the axes and driving source of each outflow with their kinematic properties found in the channel maps and PVDs.

In Figure 10, we present a schematic drawing showing an overall distribution of outflows and YSO candidates around LkH α 234. The outflow axes and positions of the emission peaks are also indicated in the figure. Figure 3 showed that the axis with P.A. = 240° traces strong [Fe II] emission and weak H_2 emission. It is aligned well with the position of radio continuum source VLA 3B, indicating that this outflow is driven by VLA 3B. This result agrees with the idea from the previous study in Paper I, which argued that the high-velocity [Fe II] jet ($V_{\text{LSR}} = -120 \text{ km s}^{-1}$) is driven by radio continuum source VLA 3B, based on its positional agreement with the radio thermal jet around VLA 3B (Trinidad et al. 2004), which has a P.A. of $\sim 230^\circ$. The inclination angle of this outflow is unknown. We assume that this outflow is toward us rather than close to the sky plane, because the observed radial velocity is highest with $\sim -150 \text{ km s}^{-1}$ among the sources in this area.

The axis with a P.A. of 225° traces the H_2 jet, which has been observed in the narrowband H_2 image by Cabrit et al. (1997). The axis of this jet is aligned well with the embedded source FIRS1-MM1 (Fuente et al. 2001; Girart et al. 2016). This outflow is traced in all three knots. The blueshifted peaks B and C and peak A2' are in good agreement with this axis. We note that A2' is redshifted with respect to the systemic velocity ($V_{\text{sys}} = -11.5 \text{ km s}^{-1}$). In Paper I, we noted this redshifted component with low velocity ($V_{\text{LSR}} < +50 \text{ km s}^{-1}$) at the position of knot A, and we proposed that it is an outflow with a wide opening angle with the axis close to the sky plane. With an assumption that this emission comes from a part of the

Figure 9. Excitation diagrams of H₂ at eight different positions around the LkH α 234 outflow. Diagrams are from (a)–(c) the redshifted knots (SP1–3), (d) knot A, (e) knot B, (f) the high-velocity shock component, (g) the PDR at systemic velocity in knot C of HH 167, and (h) the PDR ridge (SP4). The slit positions are shown in the H₂ narrowband image (Figure 1), and their position–velocity ranges are marked in Figures 4, 6, and 7. The extinction (A_K) and velocity range are shown in each panel. In all panels, the column densities are normalized to the H₂ 1–0 S(1) line. In (a)–(f), the plots are relative to the Boltzmann distribution at 2000 K. The model plots are indicated: solid, H₂ cooling zone after J-shock (Brand et al. 1988; Burton et al. 1989); dashed, C-type planar shock (Smith et al. 1991); dotted, C-type bow-shock model (Smith et al. 1991); dash-dotted, planar J-shock model with conventional cooling (Burton et al. 1989; Smith et al. 1991). In (c), populations at single temperatures of 400, 1000, 2000, and 3000 K are shown with solid straight lines.

Figure 10. Schematic diagram of multiple outflows around LkH α 234. The crosses and solid arrows show the locations of YSOs and axes of the outflows, respectively. The regions within the thin and thick solid contours represent the 3σ level of H $_2$ 1–0 S(1) and [Fe II] 1.644 μ m emission, respectively. Peaks A1' and A2' and knots B and C are marked. The area of spectral mapping is marked with a dashed rectangle. The position of the blueshifted [S II] jet is taken from Ray et al. (1990). Two red dashed arrows are extensions of the blueshifted emission, which has a P.A. of 240 and 225.

FIRS1-MM1 jet, it could arise from a wide-angle outflow showing both blue and redshifted components close to the source. On the other hand, we argue for a possible association between this redshifted H $_2$ emission and the radio continuum source VLA 2. Water masers have been detected around VLA 2 (Trinidad et al. 2004; Marvel 2005; Torrelles et al. 2014). The proper motion and locations of the masers indicate that VLA 2 has a bipolar outflow in the northeast–southwest direction, with the redshift lobe toward the southwest. Torrelles et al. (2014) estimated the inclination angle of the outflow as about 15° with respect to the plane of the sky. Girart et al. (2016) also reported the larger-scale SiO outflow, which might be a counterpart of the H $_2$ O masers. Peak A2' is located on the extension of the axis of the H $_2$ O masers, which is aligned with the FIRS1-MM1 jet, too.

From the discussion above, we suggest several possible origins of the emission from A2'. First, the emission could originate from the outflow driven by VLA 2. In this case, the emission is a newly found near-IR counterpart of that outflow. Second, it could be part of the FIRS1-MM1 jet. Third, the multiple contributions of both VLA 2 and FIRS1-MM1 could cause the emission in knot A. Peak A2' could be a place where two outflows with different axes are interacting with each other, causing the bright shock emission.

The driving source of the H $_2$ emission in peak A1' is not clear from the given positional information. We assume it is originated from VLA 2 or 3 (Trinidad et al. 2004; Girart et al. 2016) based on its proximity to those sources. An additional study with higher spatial resolution would help further our understanding of the origin of this shocked emission.

Optical [S II] emission traces axes of 240° and 225° (Ray et al. 1990). In Paper I, we assumed that the optical [S II] jet is driven by VLA 2. The origin of the [S II] outflow, however, is not clear because it shows different axes in the inner and outer regions (Ray et al. 1990). High-resolution narrowband imaging around the central sources is required to reveal their origin. We should not rule out the possibility that [S II] emission arises from multiple outflows, and the source of the emission in the inner and outer regions could be different. On the other hand, we show that the line ratios for H $_2$ indicate largely variable A_V , in the range of $0 < A_V < 40$ in the blueshifted components, although the uncertainties are larger in the regions with higher A_V . The presence of optical lines from shocks in this region is a clear indication that extinction is highly variable, perhaps also clumpy.

The blueshifted emission in the high velocity of $V_{LSR} > -100 \text{ km s}^{-1}$ with a large variation in A_V is associated with VLA 3B. In contrast to the high-velocity components, extinction and its variation are relatively small ($0 < A_V < 10$) in the velocity range of $-70 \text{ km s}^{-1} < V_{LSR} < -10 \text{ km s}^{-1}$, where the emission is mostly from the MM1 outflow (see Figures 3 and 8). The redshifted outflow, which is probably driven by VLA 2, also shows a small extinction value, with $A_V < 10$. This extinction trend contrasts with the Orion KL outflow discussed in Oh et al. (2016a), which showed relatively small extinction ($A_V \sim 0$) at the highest blueshifted velocity and larger A_V values at redshifted velocities, implying a differential extinction along the line of sight. Orion KL is a huge outflow system with more than 100 bullets ejected radially from a single origin (Bally et al. 2015; Youngblood et al. 2016). The LkH α 234 system, however, likely shows a

more complex distribution of extinction because different sources emanate multiple outflows with different axes. In addition, the distributions of dust filaments detected by Girart et al. (2016) showed that the dust emission is strongest around VLA 3 and weaker in the northwest. The extinction in the channel maps showed that A_V is highest in the southeast (the upper left part of the channel maps), which is in agreement with the dust distribution shown in Girart et al. (2016).

4.2. Multiple Counter Jets

In Section 3.2, the redshifted knots observed in SP1–3 show different velocities. The emission from SP2 and SP3 shows an especially large difference in the peak velocity, $V_{\text{LSR}} \sim +100$ and -2 km s^{-1} , despite their similar distance from the sources. This is an additional argument for multiple outflows indicating that they are the red counterparts of the multiple blueshifted outflows, because the outflows usually are bipolar phenomena. From its similarity to the velocity found in this study, the high-velocity knot in SP2 with $V_{\text{LSR}} \sim +100 \text{ km s}^{-1}$ is probably the redshifted counterpart of the blueshifted jet driven by VLA 3B with $V_{\text{LSR}} \sim -100 \text{ km s}^{-1}$. The position of this knot, which is at P.A. $\sim 35^\circ$ from VLA 3 (see Figure 10), also supports that this could be a counterpart of the VLA 3B jet. In the case of the knot at SP3, it can be matched with two counter-outflows, the MM1 jet and the radio jet of VLA 1 (Trinidad et al. 2004). Since the SP3 knot is located at P.A. $= 40^\circ$ from MM1, we suppose it is most convincing that this is a red counterpart of the MM1 jet with P.A. $= 225^\circ$. Its low radial velocity ($V_{\text{LSR}} \sim -2 \text{ km s}^{-1}$) also supports this idea, given that the MM1 jet is dominant in low velocity. The SP3 knot is also on the extended axis of the radio jet detected around VLA 1 with P.A. $= 45^\circ$ (Trinidad et al. 2004), indicating that VLA 1 could be another candidate for the origin of this redshifted emission.

The driving source of the knot at SP1 could be the same as that of SP2, because they show similar velocities. However, SP1 is located much farther from the YSO candidates than SP2. We note that the shocked H_2 emission at SP1 is spread over a very wide region, as shown by Eislöffel (2000).

4.3. Shocked H_2 Gas

4.3.1. Excitation Diagram

From the excitation diagrams in Figure 9, we showed that the emission from outflow regions arises from the cooling by shocked H_2 gas. The model calculations of various shocks are overplotted on Figures 9(a)–(f). Solid lines indicate an empirical model with a planar J -shock cooling flow, assuming that H_2 lines dominate the cooling (Brand et al. 1988; Burton et al. 1989). Dashed and dotted lines are the C -type planar shock and bow-shock models (Smith et al. 1991), respectively. For the bow-shock model, we assumed the bow speed is 180 km s^{-1} , $n_{\text{H}} = 3 \times 10^6 \text{ cm}^{-3}$, and an ionization fraction is 3×10^{-7} (Smith et al. 1991). Dash-dotted lines show a planar J -type shock model with conventional cooling (Burton et al. 1989; Smith et al. 1991). A single model does not well reproduce the populations, except for knot A (Figure 9(d)), which shows reasonable agreement with the J -shock cooling flow model (Brand et al. 1988; Burton et al. 1989). We note that discrimination between different models is not feasible in the excitation energy range below 10,000 K.

The population of knot B is scattered in Figure 9(e) toward the bottom of the figure at an excitation energy over 10,000 K.

This scatter is not shown in knot A (Figure 9(d)). This scatter might be caused by the mixture of emission from both the outflow and the PDR, because the line intensity is integrated from low velocity ($-35 \text{ km s}^{-1} < V_{\text{LSR}} < +10 \text{ km s}^{-1}$). The population in the high-excitation range of knot C ($> 10,000 \text{ K}$) shows a trend toward planar J shock compared to other panels, indicating a possible shock-type mixture. The $[\text{Fe II}]$ emission with higher velocity detected at the position of knot C (see Figure 4(b)) supports this idea, which usually arises from J -shock regions (e.g., Pyo et al. 2002; Koo et al. 2016). In the case of the Orion KL region, associated with the formation of massive stars, the shock-type mixture is also suggested. The H_2 population from Orion KL follows two models showing similar populations: H_2 cooling flow behind the J -shock and bow-shock models (Oh et al. 2016a). The smaller number of data points in this study limits more detailed comparison of line ratios between around $\text{LkH}\alpha$ 234 and the Orion KL.

The analysis with the H_2 excitation diagram shows that only with spectroscopy can we inventory the amount of shocked material in a definitive way. We show that some of the emission seen in the imaging study is very noticeably PDR. In the case of knot C, even in the same location in the image, two different velocity-resolved components represent shocks and PDR, respectively (see Figures 9(f)–(g)). There have been several big H_2 surveys: Froebrich et al. (2011) from UKIRT, and many others, for example, and Yu et al. (1997), Eislöffel (2000), and Walawender et al. (2013). This illustration points out that spectroscopy is a critical tool to confirm whether the features identified in imaging surveys represent one or the other of these two very different physical phenomena.

4.3.2. High-velocity H_2 Emission

The maximum radial velocity of H_2 gas in HH 167 reaches over -150 km s^{-1} (see Figures 3–5). This velocity is much greater than the critical shock speed ($40\text{--}50 \text{ km s}^{-1}$) at which H_2 molecules are dissociated (Draine & McKee 1993; Hollenbach 1997). Such “supercritical-velocity” (SCV) H_2 outflows have been observed in many sources (e.g., L1551 IRS5, Davis et al. 2003; HH 7, Pike et al. 2016; Orion KL, Oh et al. 2016a; DR 21, Smith et al. 2014), and several explanations have been proposed. In the following, we briefly summarize these explanations and then discuss the origin of the SCV H_2 outflow in HH 167.

The proposed explanations for the origin of the SCV H_2 outflow may be divided into two categories, depending on whether the H_2 is assumed to be in the jet or in the swept-up ambient medium.¹² In the former explanation, the jet is molecular and the emission is from H_2 molecules in the jet heated by slow internal shock by “self-shocking.” That is, a faster wind component “catches up” to a portion of the wind that either was slower to begin with or has slowed down. Behind the bow shock, the emission can also be driven by the reverse shock due to the interaction with ambient clouds (Davis et al. 2002; Smith et al. 2014). In the latter explanation, the emission is from H_2 molecules in the swept-up ambient medium. They could be either preexisting molecules that are not dissociated or new molecules formed after the dissociation. The ambient molecular gas can be accelerated to SCV

¹² The term “outflow” often includes both the outflow/jet/wind originated from the YSO and the swept-up ambient medium. Here, in order to avoid confusion, we will use the term “jet” for the outflow/jet/wind originated from the YSO.

Figure 11. The PVD of the line ratio of H_2 2–1 S(1) / 1–0 S(1) at the selected slit position “b” from the spectral mapping of HH 167. The solid lines indicate a 3σ level of the 1–0 S(1) line. The regions within the dashed circles are used for the measurement of line ratios of the low- and high-velocity components in Figure 12. In the case of the pure C shock, the ratio is close to 0.05, while for the J shock, it becomes ~ 0.24 , according to the model calculations of Smith (1995).

($\geq 50 \text{ km s}^{-1}$) without dissociation if the Alfvén speed of the medium is very large (Smith et al. 1991) or the acceleration occurs gradually by a slowly accelerating jet (Lim et al. 2002). On the other hand, molecules can re-form in the postshock cooling layer in fast dissociative shock (Hollenbach & McKee 1989). In the latter case, since the re-formation proceeds at temperatures $\lesssim 500 \text{ K}$, the H_2 2.122 μm emission line would be weak, and the H_2 spectra are characterized by the formation pumping of H_2 so that the line ratio 1–0 S(1)/2–1 S(1) should be an order of ~ 2 –3 (Hollenbach & McKee 1989; see also Pike et al. 2016 and references therein).

Figure 11 is a PVD of HH 167 showing the H_2 2–1 S(1)/1–0 S(1) ratio in slit position “b” obtained from our deep observation (see Section 2.2.1; see also Figure 1). This area contains both low- and high-velocity components, and we derive the H_2 2–1 S(1)/1–0 S(1) ratio of 0.09 ± 0.04 and 0.13 ± 0.05 for the gas at $V_{\text{LSR}} \sim 0$ and -80 km s^{-1} , respectively. For the gas at -113 km s^{-1} , we derive an upper limit of 0.16. The ratio of the SCV gas is somewhat higher than that of the low-velocity gas, but it is much less than what we would expect for the ratio from the re-formed molecules. This can also be seen in Figure 12, which shows the excitation diagrams for the gas at $V_{\text{LSR}} \sim 0$ and -80 km s^{-1} . The line ratios can be fit by two-temperature components at 1800–2700 K for both 0 and -80 km s^{-1} components. So again, their excitation temperatures are comparable, and there is no indication of a high-excitation level population of SCV gas due to formation pumping. For comparison, Pike et al. (2016) detected a 5000 K component in HH 7–11 and attributed it to the re-formed H_2 molecules. Therefore, with the given data in this study, the SCV H_2 emission in HH 167 is not likely from the re-formed H_2 molecules behind a fast J shock.

The above discussion leads us to conclude that the SCV H_2 emission might be from preexisting molecules swept up by a nondissociative shock either in the jet or in the ambient medium. Further observations with higher S/N including H_2 lines from higher excitation energy ($E_u/K > 30,000 \text{ K}$) would

help provide a deeper understanding of the true origin of the observed SCV gas.

4.4. Role of Multiple Outflows

There is literature going back many decades about outflows contributing to the destruction of cloud cores. Norman & Silk (1980) first investigated the importance of energy injection by stellar outflows; they analyzed winds from T Tauri stars because bipolar outflows from protostars were unknown at that time. In addition to Norman & Silk (1980), Franco (1983) and McKee (1989) found that the energy injection rate by outflows was sufficient to support star-forming clouds against collapse. Also, Offner & Chaban (2017) simulated that outflows drive turbulence in the core even if the initial magnetic field is strong and indicated that the outflows entrain about three times the mass of real launched gas. In this study and Paper I, we showed a cluster of low-to-intermediate-mass stars where each star has its own outflow, except LkH α 234, which could be in a later evolutionary stage. Intermediate-mass stars form in clusters where the total amount of material is fairly substantial. Unlike O-type stars, there is no ionizing radiation to drive the material away, and any supernova that we might get will come after quite some time. We demonstrate that, in the earliest phases, all of these stars in the cluster are working together to inject dynamical energy into the core. It is unlikely that outflow alone is sufficient to play this role, as it may not supply the random motions observed on large scales, as pointed out by Walawender et al. (2005), for example.

5. Summary

We present the results from high-resolution near-IR spectral mapping toward the multiple outflows around the LkH α 234 star formation region. We summarize the main results as follows.

1. The channel maps made from spectral mapping with high resolving power ($\Delta v = 7 \text{ km s}^{-1}$) provided ultra-narrow-band images that allowed us to distinguish multiple outflows overlapped spatially. We found that there are at least three different near-IR outflows showing similar P.A.s around LkH α 234, probably driven by embedded sources MM1, VLA 2, and VLA 3.
2. We showed that the H_2 emission arises from complex multiple outflows. All of the outflows around the LkH α 234 region show H_2 emission, while some parts of them have counterparts in [Fe II] and/or [S II] emission.
3. Low-velocity ($V_{\text{LSR}} < +50 \text{ km s}^{-1}$) redshifted H_2 emission at the base of HH 167 is aligned well with the H_2O masers around VLA 2. We suggest that this redshifted emission indicates an outflow from VLA 2, which may have an angle close to the plane of the sky.
4. We reconfirmed the P.A. of the [Fe II] jet previously detected in Oh et al. (2016a) as 240° and conclude that it is driven by the radio continuum source VLA 3B. This outflow is also detected with weak H_2 emission.
5. The first spectra of the redshifted knots to the northeast of HH 167 were obtained. Different knots show different velocities, with V_{LSR} from ~ 0 to $+100 \text{ km s}^{-1}$, indicating that they are likely the counterparts of the multiple outflows.
6. We probed the origin of the high-velocity (50 – 120 km s^{-1}) H_2 gas beyond the breakdown velocity.

Figure 12. H_2 excitation diagrams from (a) low- and (b) high-velocity components in slit position “b” shown in Figure 11. The relative H_2 intensities are measured at regions marked with circles in Figure 11. The intensity is integrated in the velocity ranges of $-40 \text{ km s}^{-1} < V_{\text{LSR}} < +10 \text{ km s}^{-1}$ and $-100 \text{ km s}^{-1} < V_{\text{LSR}} < -50 \text{ km s}^{-1}$. In both panels, the populations are fitted by two temperatures. Calculated excitation temperatures (T_e) are similar in (a) and (b), with $T_e = 1900\text{--}2000 \text{ K}$ in the low-excitation energy of $E_u < 10,000 \text{ K}$ and $T_e \sim 2600 \text{ K}$ in $10,000 \text{ K} < E_u < 20,000 \text{ K}$.

The faster H_2 gas shows higher line ratios than slow gases, implying that the shock properties of the two velocity components are different, but we could not find evidence to show if the H_2 arises from re-formed gas. The H_2 emission originating from the jet itself is still considerable.

7. Spectroscopy using ratios between many H_2 lines showed that some of the emission seen in the imaging study is clearly PDR instead of shocked gas. This result indicates that spectroscopy is a unique tool to measure the amount of shocked material in a definitive way.

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Software: Plotspec (Kaplan et al. 2017), IGRINS Pipeline Package (Lee et al. 2017), SAOImage DS9 (Smithsonian Astrophysical Observatory 2000), IRAF (Tody 1986, 1993).

ORCID iDs

Heeyoung Oh <https://orcid.org/0000-0002-0418-5335>
 Tae-Soo Pyo <https://orcid.org/0000-0002-3273-0804>
 Bon-Chul Koo <https://orcid.org/0000-0002-2755-1879>
 Kyle F. Kaplan <https://orcid.org/0000-0001-6909-3856>

Yong-Hyun Lee <https://orcid.org/0000-0003-3277-2147>
 Kimberly R. Sokal <https://orcid.org/0000-0002-3621-1155>
 Gregory N. Mace <https://orcid.org/0000-0001-7875-6391>
 Jae-Joon Lee <https://orcid.org/0000-0003-0894-7824>
 Narae Hwang <https://orcid.org/0000-0002-2013-1273>
 Hwihyun Kim <https://orcid.org/0000-0003-4770-688X>
 Daniel T. Jaffe <https://orcid.org/0000-0003-3577-3540>

References

- Bally, J., Ginsburg, A., Silvia, D., & Youngblood, A. 2015, *A&A*, **579**, A130
 Bally, J., & Reipurth, B. 2001, *ApJ*, **546**, 299
 Bally, J., Reipurth, B., & Davis, C. J. 2007, in *Protostars and Planets V*, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 215
 Beckwith, S., Persson, S. E., Neugebauer, G., & Becklin, E. E. 1978, *ApJ*, **223**, 464
 Black, J. H., & van Dishoeck, E. F. 1987, *ApJ*, **322**, 412
 Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, *MNRAS*, **285**, 201
 Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 2001, *MNRAS*, **323**, 785
 Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, *MNRAS*, **298**, 93
 Brand, P. W. J. L., Moorhouse, A., Burton, M. G., et al. 1988, *ApJL*, **334**, L103
 Burton, M., Brand, P., Moorhouse, A., & Geballe, T. 1989, in *ESA SP-290, Infrared Spectroscopy in Astronomy*, ed. B. H. Kaldeich (Noordwijk: ESA), 281
 Cabrit, S., Lagage, P.-O., McCaughrean, M., & Olofsson, G. 1997, *A&A*, **321**, 523
 Davis, C. J., Ray, T. P., Eisloffel, J., & Corcoran, D. 1997, *A&A*, **324**, 263
 Davis, C. J., & Smith, M. D. 1996, *A&A*, **309**, 929
 Davis, C. J., Stern, L., Ray, T. P., & Chrysostomou, A. 2002, *A&A*, **382**, 1021
 Davis, C. J., Whelan, E., Ray, T. P., & Chrysostomou, A. 2003, *A&A*, **397**, 693
 Draine, B. T., & McKee, C. F. 1993, *ARA&A*, **31**, 373
 Edwards, S., & Snell, R. L. 1983, *ApJ*, **270**, 605
 Eisloffel, J. 2000, *A&A*, **354**, 236
 Franco, J. 1983, *ApJ*, **264**, 508
 Froebrich, D., Davis, C. J., Ioannidis, G., et al. 2011, *MNRAS*, **413**, 480
 Fuente, A., Neri, R., Martín-Pintado, J., et al. 2001, *A&A*, **366**, 873
 Girart, J. M., Torrelles, J. M., Estalella, R., et al. 2016, *MNRAS*, **462**, 352
 Hartigan, P., Edwards, S., & Ghandour, L. 1995, *ApJ*, **452**, 736
 Hartigan, P., Morse, J. A., Reipurth, B., Heathcote, S., & Bally, J. 2001, *ApJL*, **559**, L157
 Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J. 1992, *ApJ*, **397**, 613
 Hogerheijde, M. R., Jansen, D. J., & van Dishoeck, E. F. 1995, *A&A*, **294**, 792

- Hollenbach, D. 1997, in IAU Symp. 182, Herbig–Haro Flows and the Birth of Stars, ed. B. Reipurth & C. Bertout (Dordrecht: Kluwer), 181
- Hollenbach, D., & McKee, C. F. 1989, *ApJ*, 342, 306
- Houck, J. R., Roellig, T. L., Van Cleve, J., et al. 2004, *Proc. SPIE*, 5487, 62
- Kaplan, K. F., Dinerstein, H. L., Oh, H., et al. 2017, arXiv:1701.05604
- Kato, E., Fukagawa, M., Perrin, M. D., et al. 2011, *PASJ*, 63, 849
- Koo, B.-C., Raymond, J. C., & Kim, H.-J. 2016, *JKAS*, 49, 109
- Lee, J.-J., Gullikson, K., & Kaplan, K. 2017, *igrins/plp* 2.2.0, Zenodo, doi:10.5281/zenodo.845059
- Lim, A. J., Raga, A. C., Rawlings, J. M. C., & Williams, D. A. 2002, *MNRAS*, 335, 817
- Mace, G., Kim, H., Jaffe, D. T., et al. 2016, *Proc. SPIE*, 9908, 99080C
- Marvel, K. B. 2005, *AJ*, 130, 2732
- McGroarty, F., Ray, T. P., & Bally, J. 2004, *A&A*, 415, 189
- McKee, C. F. 1989, *ApJ*, 345, 782
- Morris, P. W., Noriega-Crespo, A., Marleau, F. R., et al. 2004, *ApJS*, 154, 339
- Movsessian, T. A., Magakian, T. Y., Bally, J., et al. 2007, *A&A*, 470, 605
- Norman, C., & Silk, J. 1980, *ApJ*, 238, 158
- Offner, S. S. R., & Chaban, J. 2017, *ApJ*, 847, 104
- Oh, H., Pyo, T.-S., Kaplan, K., et al. 2016a, *ApJ*, 833, 275
- Oh, H., Pyo, T.-S., Yuk, I.-S., et al. 2016b, *ApJ*, 817, 148 (Paper I)
- Park, C., Jaffe, D. T., Yuk, I.-S., et al. 2014, *Proc. SPIE*, 9147, 91471D
- Petersen, L., & Gammelgaard, P. 1996, *A&A*, 308, 49
- Pike, R. E., Geballe, T. R., Burton, M. G., & Chrysostomou, A. 2016, *ApJ*, 822, 82
- Pineda, J. E., Offner, S. S. R., Parker, R. J., et al. 2015, *Natur*, 518, 213
- Pyo, T.-S., Hayashi, M., Kobayashi, N., et al. 2002, *ApJ*, 570, 724
- Pyo, T.-S., Kobayashi, N., Hayashi, M., et al. 2003, *ApJ*, 590, 340
- Ray, T. P., Poetzel, R., Solf, J., & Mundt, R. 1990, *ApJL*, 357, L45
- Reipurth, B., Heathcote, S., Morse, J., Hartigan, P., & Bally, J. 2002, *AJ*, 123, 362
- Rieke, G. H., & Lebofsky, M. J. 1985, *ApJ*, 288, 618
- Schultz, A. S. B., Rank, D., Temi, P., & Harker, D. 1995, *Ap&SS*, 233, 71
- Shevchenko, V. S., & Yakubov, S. D. 1989, *AZh*, 66, 718
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
- Smith, M. D. 1995, *A&A*, 296, 789
- Smith, M. D., Brand, P. W. J. L., & Moorhouse, A. 1991, *MNRAS*, 248, 730
- Smith, M. D., Davis, C. J., Rowles, J. H., & Knight, M. 2014, *MNRAS*, 443, 2612
- Smithsonian Astrophysical Observatory 2000, SAOImage DS9: A Utility for Displaying Astronomical Images in the X11 Window Environment, Astrophysics Source Code Library, ascl:0003.002
- Starr, B. M., Doyon, R., Beuzit, J.-L., et al. 2000, *Proc. SPIE*, 4008, 999
- Tody, D. 1986, *Proc. SPIE*, 627, 733
- Tody, D. 1993, *adass II*, 52, 173
- Torrelles, J. M., Curiel, S., Estalella, R., et al. 2014, *MNRAS*, 442, 148
- Trinidad, M. A., Curiel, S., Torrelles, J. M., et al. 2004, *ApJ*, 613, 416
- Turner, J., Kirby-Docken, K., & Dalgarno, A. 1977, *ApJS*, 35, 281
- Walawender, J., Bally, J., & Reipurth, B. 2005, *AJ*, 129, 2308
- Walawender, J., Reipurth, B., & Bally, J. 2013, *AJ*, 146, 66
- Youngblood, A., Ginsburg, A., & Bally, J. 2016, *AJ*, 151, 173
- Yu, K. C., Bally, J., & Devine, D. 1997, *ApJL*, 485, L45
- Yuk, I.-S., Jaffe, D. T., Barnes, S., et al. 2010, *Proc. SPIE*, 7735, 77351M
- Zinnecker, H., & Yorke, H. W. 2007, *ARA&A*, 45, 481