THE INTRIGUING GIANT BOW SHOCKS NEAR HH 131

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ABSTRACT

Using the High Dispersion Spectrograph (HDS) at the Subaru Telescope, echelle spectra of two giant arcs, i.e., nebulosities Cw and L associated with HH 131 in Orion are presented. Typical emission lines of Herbig-Haro (HH) objects have been detected toward nebulosity Cw with the broadband filter KV 408. With the low-dispersion spectrograph at the National Astronomical Observatories (NAO) 2.16 m telescope, spectra of nebulosities C, L, and K are obtained, which also show strong [S ii] 6717/6731, Hα, and [N ii] 6583 emission lines. Position-velocity distributions of Cw and L are analyzed from the long-slit spectra observed with the HDS Hα narrowband filter. The fastest radial velocity of Cw is $V_r \sim -18.0$ km s$^{-1}$. When the flow at L goes to the south, it slows down. The fastest radial velocity of L has been observed at $-45.0$ km s$^{-1}$, and the slowest value is about $-18.3$ km s$^{-1}$; the radial velocity gradient is about 200 km s$^{-1}$ pc$^{-1}$. The similarity of the fastest radial velocity of Cw to the slowest value of L and their positional connection indicate that they are physically associated. There is a tendency for the entire flow to become less excited and less ionized when going further to the south (i.e., from nebulosities K to L and C), where the most extended (and presumably evolved) objects are seen. The electron densities of all the observed nebulosities are low ($n_e \sim 10^2$ cm$^{-3}$). Double-peaked kinematic signatures have been found in Cw from its [N ii] 6583 profiles, while the observed Hα profiles of Cw are almost symmetric. Bow shock models appear to agree with the observed position-velocity diagrams of the [N ii] spectra better than Hα spectra, and a bow shock with its wing, apex, and postshock has been possibly revealed near Cw from the [N ii] emission. With the suggestion that these arcs are HH shocks possibly ejected out of the Orion A molecular cloud by an uncertain source, their spectra show low to intermediate excitation from their diagnostic line ratios.

Key words: ISM: Herbig-Haro objects — ISM: individual (HH 131) — ISM: jets and outflows

1. INTRODUCTION

Mass outflows emerge from young stellar objects (YSOs) at very early stages of star formation processes. Mass outflows are traced by Herbig-Haro (HH) objects at optical wavelengths, while molecular hydrogen and [Fe ii] emission are seen at near-infrared wavelengths. At millimeter wavelengths bipolar molecular outflows are best observed in the lines of CO. HH objects are collisionally excited nebulae produced by outflows ejected by YSOs, and they trace either shocks in which outflows ram the quiescent interstellar medium (terminal working surfaces) or shocks produced by colliding fluid elements ejected from the source at different velocities and times (internal working surfaces) (Raga et al. 1990). The conception of parsec-scale HH flows has altered our understanding of optical jets and HH objects since Bally and Devine first discovered the giant HH 34 flow, which extends about 3.4 pc (Bally & Devine 1994; Reipurth et al. 1997; Devine 1997). The total extension of an HH flow is much larger than originally thought (Mundt & Fried 1983), surpassing 1 pc in most cases. Thanks to the technical development of larger CCD arrays, wide-field surveys of optical outflows have been recently carried out covering dozens of square degrees in nearby star-forming regions (Yan et al. 1998; Zhao et al. 1999; Yang & Yao 2000; Wang et al. 2000, 2001; Wu et al. 2002; Sun et al. 2003; Walawender et al. 2005). Spectrographic measurements and analyses in terms of bow shock models provide a comprehensive picture of the outflow phenomenon of YSOs (Schwartz 1975; Hartigan et al. 1987; Raga et al. 1996). However, it is not yet clear how far the parsec-scale HH objects impact on the surrounding interstellar medium (ISM). HH 131 and its nearby giant bow shocks possibly provide the most intriguing targets, which are located well outside the Lynds 1641 (hereafter L1641) dark cloud, i.e., about 1.5 southwest of L1641. In L1641 not only the largest number of HH objects (in all 70 from the list by Reipurth [1999]) and the prototypical HH objects, HH 1 and HH 2, but also the first parsec-scale HH flow, HH 34, have been discovered. All these HH objects are situated inside or very close to the boundary of the Orion A giant molecular cloud (GMC). With narrowband imaging Ogura (1991) discovered HH 131 and some large nebulosities like A, B, C, ... K, and L and suggested that those nebulosities might be physically HH objects. The linear scale of a single bow shock of them is even larger than 3 pc (We adopt a distance of 450 pc.) Intending to study their nature, with the Subaru Telescope we have made spectrographic observations toward Cw and L. Cw is located slightly west to the given position of C (see the image shown in Fig. 1, which was derived with the 0.6/0.9 cm Schmidt telescope at Xinglong Station of the National Astronomical Observatories [NAO], Chinese Academy of Sciences). Low-dispersion spectra of C, L, and K were also obtained with the spectrograph mounted at the NAO 2.16 m telescope.

2. OBSERVATION AND DATA REDUCTION

With the High Dispersion Spectrograph (HDS; Noguchi et al. 2002) at the Subaru Telescope, the observations of nebulosities

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Cw and L were carried out on the night of 2001 October 22/23. The filters used in the observations were a broadband one named StdYc or KV 408 and a narrowband one named StdHa or Hα.

Table 1 lists the observing targets and instrumental parameters. The slit with a width of 1.0 provided a spectral resolution of 36,000, corresponding to a velocity resolution of 8.3 km s⁻¹, which was confirmed by sky lines. The observed spectra were wavelength calibrated using exposures to a Th-Ar comparison lamp. The accuracy of wavelength calibration is better than 0.01 Å, or 0.5 km s⁻¹ at Hα.

We obtained spectra for Cw with the KV 408 filter; the slit length was set as 500, and the exposure time was 1800 s. Flux calibration was achieved using echelle spectra of the standard star HZ 15 (Stone 1977), and its exposure time was 120 s. The wavelength range covered 4390–5710 and 5810–7130 Å for CCD1 and CCD2, respectively. The linear dispersion of the CCD near 6600 Å was ~0.04 Å pixel⁻¹, or 1.8 km s⁻¹.

Narrowband long-slit spectra were taken for Cw and L (see Fig. 1) with the slit at position angles of 0° and 150°, respectively. The slit length was 60″. The StdHa/Hα filter was used, which was centered on 6580 Å with a passband of 54.6 Å, covering the Hα and [N ii] λλ6548, 6583 emission lines. The integration time of each position was 2.5 hr. The angular scale on the CCD frame was ~0″27 pixel⁻¹ along the direction of the slit (CCD 2 × 2 binning mode used).

Except for overscanning, which was dealt with using a procedure provided by the Subaru project group, data reduction has been made with the IRAF package, including bias subtraction.

TABLE 1
LOG OF OBSERVATIONS

| Object | α(J2000.0)  | δ(J2000.0) | Slit P.A. (deg) | Slit Length (arcsec) | Exp. Time (s) | Filter        |
|--------|-------------|------------|---------------|---------------------|--------------|---------------|
|        |             |            |               |                     |              | Spectrograph at NAO 2.16 m |
| C      | 05 33 51.36 | −08 42 38.7 | 0             | 240                 | 1800 x 3     |               |
| L      | 05 34 27.12 | −08 34 24.3 | 0             | 240                 | 1800 x 1     |               |
| K      | 05 34 19.37 | −08 32 01.7 | 0             | 240                 | 1800 x 1     |               |
|        |             |            |               |                     |              | HDS at SUBARU 8.2 m |
| Cw     | 05 33 48.98 | −08 42 45.6 | 0             | 5                   | 1800 x 1     | KV 408        |
| Cw     | 05 33 49.04 | −08 42 46.5 | 0             | 60                  | 1800 x 2     | Hα            |
| L      | 05 34 26.27 | −08 34 18.0 | 150           | 60                  | 1800 x 2     | Hα            |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
flat-fielding, spectra extraction, wavelength and flux calibrations, and velocity corrections. For the observations with the Hα filter, wavelength calibration has to be made according to two echelle orders (order 91 and 90) separately instead of just for order 91. We then co-add these two calibrated spectra into one spectrum (A. Wako & A. Tajitsu 2004, private communication).

In data reduction we noticed the problem caused by contamination from sky-line emission. Because of the limited slit length used for the broadband mode, subtraction of the sky emission spectrum was impossible, since the observed object fills the entire slit aperture. In the case of the narrowband mode, the sky emission was possibly subtracted, because the relatively much longer slit aperture used was covering regions where the signal from the object was much weaker than that at peak. These regions were taken for establishing the “sky spectrum” (including a small contribution from the extended object), which was then subtracted from the “object spectrum.” As a consequence, the sky emission could be slightly over- or undersubtracted (see little tips or valleys at $\sim 20$ km s$^{-1}$ in Figs. 7 and 8).

Low-dispersion spectroscopic observations of nebulosities C, L, and K were made with the NAO 2.16 m reflector using a Cassegrain spectrograph during 1999 December 5–9. The grating used was 100 lines mm$^{-1}$. The slit was 4′ long with a width of 2′. The resulting spectral resolution is $\sim 7$ Å. All slit orientations followed the north-south direction.

3. RESULTS AND DISCUSSIONS

3.1. Emission Lines

3.1.1. Low-Dispersion Spectra

Figure 2 displays the low-resolution spectra of nebulosities C, L, and K, which were observed with the NAO 2.16 m
telescope. Line identifications and integrated line intensities are presented in Table 2. The [S\textsc{ii}] $\lambda\lambda 6717, 6731$, H$\alpha$, and [N\textsc{ii}] $\lambda 6583$ lines have been clearly detected and show strong emission toward all three nebulosities. Although the detections of [N\textsc{ii}] $\lambda 6548$ and H$\beta$ are certain, there are larger uncertainties in their line intensities than in the former four lines. The detection of [O\textsc{i}] $\lambda 6300$ emission from L is tentative due to strong contamination of sky light. Continuum emission was not detected from any of the three nebulosities. The clearly detected emission lines toward C, L, and K are characteristic signatures of HH objects with strong forbidden lines and no continuum emission. No reddening correction has been applied to the emission-line intensities through the entire paper. Such a correction is not critical in the interpretation of line ratios that are close in wavelength, e.g., those of H$\alpha$ to [S\textsc{ii}] or [S\textsc{ii}] $\lambda 6717/6731$.

The electron densities ($n_e$) listed in Table 2 have been deduced from the [S\textsc{ii}] $\lambda 6717/6731$ line intensity ratios, assuming an electron temperature of 10,000 K (Osterbrock 1989). They tend to decrease from about 400 cm$^{-3}$ for K to around 40 cm$^{-3}$ for L and C.

### 3.1.2. HDS Spectra

Toward Cw, the [S\textsc{ii}] $\lambda 6717, 6731$, H$\alpha$, [N\textsc{ii}] $\lambda 6548, 6583$, [O\textsc{i}] $\lambda 6300, 6363$, and H$\beta$ emission lines have been detected in our HDS echelle spectra (Fig. 3). Continuum emission was not detected. The H$\alpha$ and H$\beta$ lines present broader profiles than those of [S\textsc{ii}] and [N\textsc{ii}], while the case of the [O\textsc{i}] $\lambda\lambda 6300, 6363$ lines is less clear. Gaussian fitting parameters are given in Table 3. The detected lines suggest that nebulosity Cw possesses quite a complex kinematic structure. At least two velocity components are seen at about $-15$ km s$^{-1}$ (all velocities are heliocentric unless otherwise noted) and 0 km s$^{-1}$, respectively. There is likely also a third component around $20-27$ km s$^{-1}$, which is most likely from the sky emission, or partly from the Orion star-forming region. So the giant bow shock Cw is slightly moving toward us with the extreme velocity of $-17.5$ km s$^{-1}$ seen in the [N\textsc{ii}] $\lambda 6583$ emission line. The complex velocity structure of Cw is discussed in detail in § 3.3.

The [S\textsc{ii}], [N\textsc{ii}], and [O\textsc{i}] lines all have all emission peaks at about $-15$ km s$^{-1}$ (in Table 4). From the line-emission peak intensities, we estimate that [S\textsc{ii}] $\lambda\lambda(6717 + 6731)/H\alpha \sim 1.55$ and [N\textsc{ii}] $\lambda\lambda(6717 + 6731) \sim 0.41$. According to the integrated fluxes (in Table 3), [S\textsc{ii}] $\lambda\lambda(6717 + 6731)/H\alpha \sim 1.54$ (1.33 without the third velocity component included, and the third component of H$\alpha$ is never counted for ratio calculations because of the certainty of H$\alpha$ emission from the sky) and [N\textsc{ii}] $\lambda 6583/[S\textsc{ii}] \lambda\lambda(6717 + 6731) \sim 0.38(0.31)$.

According to the total fluxes, [S\textsc{ii}] $\lambda\lambda 6717/6731 \sim 1.34(1.37)$. From the peak intensities in Table 4, [S\textsc{ii}] $\lambda\lambda 6717/6731 \sim 1.26$. This implies that the electron density is about 80–170 cm$^{-3}$. The nondetection of [O\textsc{i}] $\lambda 5007$ implies that the shock velocity is less than 100 km s$^{-1}$ (Hartigan et al. 1987).

### 3.2. What Is the Nature of the Nebulosities?

In order to explore the true nature of these nebulosities we have plotted the line ratios of H$\alpha$/[S\textsc{ii}] $\lambda\lambda(6717 + 6731)$ versus the ratios of [S\textsc{ii}] $\lambda\lambda 6717/6731$ for nebulosities C, Cw, L, and K in Figure 4, comparing them with those of HH objects, compiled by Raga et al. (1996), and planetary nebulae (PNe), supernova remnants (SNRs), and H\textsc{ii} regions (adopted from the figures by Sabband et al. [1977] and Meaburn & White [1982]). Similar to the morphology displayed in Figure 1, in Figure 4 nebulosities Cw (C), L, and K present a physical nature very close to that of SNRs and far from that of H\textsc{ii} regions or PNe. The strong [S\textsc{ii}] $\lambda\lambda 6717/6731$ and the nondetection of [O\textsc{i}] $\lambda 5007$ suggest that nebulosities Cw (C), K, and L cannot be SNRs (Fesen et al. 1985; Fesen & Hurford 1996). Therefore, we suggest that these nebulosities are HH shocks. In Figure 4 nebulosities Cw (C), K, and L have line ratios similar to those of HH 125 I–K, HH 131, HH 128, HH 111 L, HH 235 (or GGD 35), HH 34 MD, and HH 124 A–C. It is especially interesting that HH 125 and HH 124 also present large bow shocks (Walsh et al. 1992). HH 128, HH 34 MD, HH 111 L, and possibly HH 235 are parts of individual parsec-scale HH objects (Reipurth et al. 1997; Ray et al. 1990). One giant part of the HH 111 flow, i.e., HH 311, extends out to 5.0 pc at a distance of 450 pc (Reipurth et al. 1997), which has been previously thought of as the largest extension of an HH bow shock. Nebulosity C is much larger than HH 311.

Raga et al. (1996) made statistics for a large fraction of optical spectra of HH objects and derived a quantitative criterion to divide HH spectra into high-, intermediate-, and low-excitation categories. A dashed vertical line in Figure 4 shows the division of high/intermediate excitation (to the right side) and low excitation of HH spectra (to the left side) according to the line ratio of [S\textsc{ii}] $\lambda\lambda(6717 + 6731)/H\alpha$ with a value of 1.5. The intensity ratios of [S\textsc{ii}] $\lambda\lambda(6717 + 6731)/H\alpha$ are 1.6, 1.4, and 0.9 for nebulosities C (Cw), L, and K, respectively. With the clear criterion and the nondetection of [O\textsc{i}] $\lambda 5007$, their spectra show low to intermediate excitation. The excitation tends to decrease from nebulosities K to L and C, that is, there is a tendency for the flow to become less excited when going further to the south.

### 3.3. Position-Velocity Distributions of Nebulosities Cw and L

Figures 5 and 6 display the position-velocity diagrams obtained from the long-slit spectra of nebulosities Cw and L, respectively. We have detected three emission lines, H$\alpha$ at 6563 Å and [N\textsc{ii}] at 6583 and 6548 Å. [N\textsc{ii}] $\lambda 6548$ is the faintest of the three lines, only clearly seen at the brightest positions with the relative position (hereafter denoted as Y) at $-6^\circ$ to $0^\circ$ for both Cw and L, and is thus not displayed or further analyzed. For each line one component ($V_1$) at $20-25$ km s$^{-1}$ is relatively homogeneous through the entire slit and has been identified as sky emission (Figs. 5 and 6). Similar velocity values of [N\textsc{ii}] $\lambda 6548$ and [S\textsc{ii}] $\lambda 6717, 6731$ have also been estimated in Table 3. In

### Table 2

| Identification | Integrated Intensity $^a$ |
|----------------|---------------------------|
|                | C  | L  | K  |
| H$\beta$ $\lambda 4861$ | 39$^b$ | 39$^b$ | 71$^b$ |
| [O\textsc{i}] $\lambda 6300$ | 29$^b$ | 29$^b$ | 29$^b$ |
| [N\textsc{ii}] $\lambda 6548$ | 17$^b$ | 19$^b$ | 16$^b$ |
| H$\alpha$ $\lambda 6583$ | 100 | 100 | 100 |
| [N\textsc{ii}] $\lambda 6583$ | 62 | 57 | 42 |
| [S\textsc{ii}] $\lambda 6717$ | 95 | 79 | 50 |
| [S\textsc{ii}] $\lambda 6731$ | 64 | 57 | 39 |
| $n_e$(cm$^{-3}$)$^c$ | <40 | 40 | 400 |

$^a$ Integrated intensities of H$\alpha$ of nebulosities C, L, and K are 8.7 x 10$^{-15}$, 4.4 x 10$^{-15}$, and 4.3 x 10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$, respectively.

$^b$ Uncertain.

$^c$ Electron densities according to the line ratios of [S\textsc{ii}] $\lambda 6717/6731$ (Osterbrock 1989).
Fig. 3.—HDS echelle line spectra of nebulosity Cw obtained with the filter StdYc or KV 408. Exposure time is 1800 s.
Figure 5 the other two velocity components are clearly seen in [N II] toward Cw. One is at about 0 km s\(^{-1}\) (\(V_2\)), and the other is around −15 km s\(^{-1}\) (\(V_1\)). The \(V_2\) component appears to be blended with some background emission, which possibly represents emission from the local star-forming region. The \(V_1\) component is also likely contaminated with a fainter, yet similar background. At H\(\alpha\) a bright feature has been observed at the same position as the [N II] line with \(V_0\) around 0\(^0\). However, the two velocity components have not been discerned at H\(\alpha\), while the background is strong. In Figure 6 it is shown that the position-velocity diagrams of both H\(\alpha\) and [N II] of L are different from Cw. They present less complex velocity features showing that the emission is possibly from several spatially separate parts. Dividing each line into 20 spatially equal parts (each part corresponds to 3\(^0\)), spectra have been extracted. Figures 7 and 8 give their profiles with the sky-emission component (\(V_2\)) subtracted in the way described in § 2.

![Diagram](image)

**Figure 4.** Diagrams of log H\(\alpha\) vs. [S II] \(\lambda\lambda(6717 + 6731)\) vs. [S II] \(\lambda\lambda(6717 + 6731)\) for various emission-line objects. The positions of nebulesities C, Cw, L, and K are indicated with crosses. HH objects are indicated with filled circles (data from the compilation by Raga et al. 1996); some well-known HH objects are labeled. The regimes of PN, SNR, and H\(\alpha\) regions (adopted from the figures by Sabbadin et al. [1977] and Meaburn & White [1982]) are marked. The dashed vertical line gives the division between high/intermediate and low excitation of HH objects.

### TABLE 3

| Line | Center (Å) | Core (10\(^{-16}\) ergs cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)) | FWHM (Å) | Flux (10\(^{-16}\) ergs cm\(^{-2}\) s\(^{-1}\)) | \(V_0\) (km s\(^{-1}\)) |
|------|------------|----------------|----------|----------------|------------------|
| H\(\beta\) | 4861.058 | 11.07 | 0.401 | 4.72 ± 1.13 | −16.17 |
| H\(\alpha\) | 6562.699 | 17.79 | 0.823 | 12.55 ± 0.28 | 1.27 |
| [O I] \(\lambda\) 6300 | 6299.996 | 5.01 | 0.234 | 1.25 ± 0.21 | −14.67 |
| [O I] \(\lambda\) 6363 | 6363.738 | 2.41 | 0.104 | 0.27 ± 0.11 | −1.79 |
| [N II] \(\lambda\) 6554 | 6548.049 | 3.12 | 0.196 | 1.47 ± 0.25 | 0.74 |
| [N II] \(\lambda\) 6583 | 6583.998 | 5.33 | 0.273 | 2.19 ± 0.32 | 24.56 |
| [S II] \(\lambda\) 6717 | 6716.097 | 24.20 | 0.290 | 7.47 ± 0.40 | −15.32 |
| [S II] \(\lambda\) 6731 | 6731.412 | 3.22 | 0.374 | 1.28 ± 0.31 | 26.94 |

**Notes:**

- \(\lambda_0\) from Table 4.
- \(\lambda_0\) from the atomic line list by the University of Kentucky (see http://www.pa.uky.edu/~peter/atomic).

### TABLE 4

| \(\lambda\) (Å) | \(\lambda_0\) (Å) | Line | Peak (10\(^{-16}\) ergs cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)) | \(V_0\) (km s\(^{-1}\)) |
|----------------|----------------|------|----------------|------------------|
| 4861.196 | 4861.32 | H\(\beta\) | 21.14 | −7.71 |
| 6329.967 | 6300.304 | [O I] \(\lambda\) 6300 | 4.58 | −15.95 |
| 6373.718 | 6548.056 | [N II] \(\lambda\) 6554 | 5.39 | −15.21 |
| 6562.679 | 6562.80 | H\(\alpha\) | 25.75 | −5.33 |
| 6583.067 | 6583.459 | [N II] \(\lambda\) 6583 | 16.28 | −17.45 |
| 6716.108 | 6716.444 | [S II] \(\lambda\) 6717 | 22.41 | −14.87 |
| 6730.543 | 6730.816 | [S II] \(\lambda\) 6731 | 17.57 | −12.17 |
Fig. 5.—HDS long-slit gray-scaled position-velocity diagrams for nebulosity Cw at (a) Hα and (b) [N ii] 6583. The vertical axis represents the slit direction (see Fig. 1), and the horizontal follows the wavelength dispersion.
In general, with increasing declination (δ), i.e., with Y increasing in Cw and decreasing in L, both Cw and L tend to have more negative velocity values (see Figs. 5–8). In the following we present and discuss their individual features in detail.

At Y = 0′0 nebulosity Cw is brightest with the velocity of $V_1 \approx -18.0 \text{ km s}^{-1}$. The emission starts to be seen at Y = -21′0 with $V_2 \approx +3.7 \text{ km s}^{-1}$. The $V_2$ component becomes brighter with increasing Y when Y = -21′′ to -15′0. At Y = -12′0 the profile shows a clearly double-peaked feature with $V_2 = -0.1 \text{ km s}^{-1}$ and $V_1 = -17.4 \text{ km s}^{-1}$. Above Y = -9′0, the $V_1$ component begins to be brighter than $V_2$, while $V_2$ gets closer and closer to $V_1$. At Y = -6′0 to 0′0 the $V_1$ emission becomes brightest, while the $V_2$ component disappears; then the $V_1$ emission gets fainter with Y increasing till it almost disappears at Y = 15′0. Hα is obviously broader than [N ii] λ6583, and likely the corresponding $V_1$ and $V_2$ components of Hα are blended; therefore, the above variations of velocities and intensities with different positions are only barely seen. Figure 9 displays the Gaussian fitting parameters of the [N ii] λ6583 profiles of Cw varying with positions, including the central velocity in (a), FWHM in (b), the relative central intensity in (c), and the peak intensity in (d) where the $V_1$ component is indicated with filled circles and the $V_2$ component with open circles.

For nebulosity L the velocity distribution is different from Cw. Except for a slight wiggle around Y = 6′, as a whole with Y increasing, the velocity decreases while the emission intensity has maxima at three positions (-33′0, -6′0, and 21′0) (see Figs. 6 and 8). At Y = -33′0, nebulosity L has its fastest velocity value of $-43.4 \text{ km s}^{-1}$ measured in [N ii] λ6583 and $-44.5 \text{ km s}^{-1}$ in Hα. The slowest velocity $V \approx -18.3 \text{ km s}^{-1}$ is reached at Y = 21′0, which approximates to $V_1$ of Cw. The fastest radial velocity of Cw is similar to the slowest value of nebulosity L. Together with their positional connection, this indicates that they are physically associated. So when nebulosity L goes further to the south, it slows down with a radial velocity gradient of 200 km s$^{-1}$ pc$^{-1}$, which is comparable to that...
of the blue or the red lobe of the HH 34 flow (Devine et al. 1997).

3.4. Comparison of Observations with Bow Shock Models

Line profiles and position-velocity diagrams have been theoretically predicted by Hartigan et al. (1987) and Raga & Böhm (1986) for a bow shock. They assume that a large fraction of the bow shock falls in the slit. In addition, they have showed that as the slit width changes the predicted line profiles alter radically, and profiles can also be significantly different from one line to the other with the same slit width (Figs. 3e, 3t, and 3v of Hartigan et al. 1987). For our case, the slits actually sample a very small region of the enormous arcs. So when we compare our observation results with their predictions, it might be reasonable that some disagreements will occur.

Hartigan et al. (1987) presented theoretical line profiles of bow shock models with different shock velocities \( V_s \) and orientations (denoted by \( \phi \), which is the angle of the plane of the sky with respect to the axis of symmetry of the bow shock). For nebulosity Cw a low shock velocity can be derived from the \([N\,\text{ii}]\) \( \lambda 6583 \) line rather than from \( \text{H}\alpha \) (shock velocity equals \( \Delta V_{\text{FWZI}} \sim 45.0 \) km s\(^{-1}\), where \( \Delta V_{\text{FWZI}} \) is the full width at zero intensity level). Double-peaked \( \text{H}\alpha \) profiles occur only when \( V_s > 150 \) km s\(^{-1}\) and \( \phi > 45^\circ \). (The expression \( \phi \) is adjusted to follow the definition by Raga & Böhm [1986].) However, such double-peaked kinematic signatures have been found in the \([N\,\text{ii}]\) \( \lambda 6583 \) profiles of Cw. The observed \( \text{H}\alpha \) profiles of Cw are almost symmetric. Comparing the computed position-velocity diagrams of \([N\,\text{ii}]\) \( \lambda 6583 \) with those of \( \text{H}\alpha \) predicted by Raga & Böhm (1986) in their Figures 2 and 3, we note that at each \( \phi \) the \([N\,\text{ii}]\) \( \lambda 6583 \) diagram has more delicate structures at peaks than \( \text{H}\alpha \), although both appear very similar. Thus, the different observation results between \([N\,\text{ii}]\) \( \lambda 6583 \) and \( \text{H}\alpha \) may be explained. When carefully comparing the computed position-velocity diagrams of \([N\,\text{ii}]\) \( \lambda 6583 \) with our observations, we do not find a certain range of \( \phi \) well constrained (or possibly \( \phi > 45^\circ \)).
According to the models of Hartigan et al. (1987), which are in general made for Hα profiles, when $\phi = 90^\circ$ the two peaks arise from different areas on the bow shock: the high radial velocity component arises from near the apex, and the low radial velocity from the wings. As $\phi$ decreases, the distinction between peaks becomes less clear, since the expansion of postshock material distributes emission over a range of radial velocities. Toward nebulosity Cw we have explicitly seen how the fast-velocity $V_1$ component and the slow $V_2$ one vary with positions in [N ii] $\lambda$6583 instead of in Hα. At $Y = -21^\prime\prime$ to $-15^\prime\prime$, [N ii] $\lambda$6583 profiles only show the slow-velocity $V_2$ component, which might be due to the wing of the shock. At $Y = -12^\prime\prime$ to $-9^\prime\prime$, the profiles are double peaked with both the slow- and the fast-velocity components ($V_2$ and $V_1$, respectively), which could be from the transition region of the wing and the apex. At $Y = -6^\prime\prime$ to $0^\prime\prime$, the profiles are brightest with only the fast-velocity $V_1$ emission that is from the shock apex. At $Y = 3^\prime\prime$ to $12^\prime\prime$, the profiles present increasingly getting weaker emission with a broader $V_1$ component, which is likely due to the expansion of postshock material. Similar analyses of velocity structures obtained with line profiles of [Fe ii] 1.644 $\mu$m lines were given by Pyo et al. (2002) for L1551 IRS 5.

3.5. Possible Origin and More on the Nature of the Giant Bow Shocks

As we have known from the prominent similarities of PNe, SNRs, H ii regions, and HH objects, and therefore lots of previous confusion, now we are about to reexamine the nature of these giant arcs. First, they are not PNe, which are usually symmetrical and possess small scales. Second, it is very unlikely for them to be from SNRs. Thus far no SNRs have been found near these arcs. Third, can they belong to the extremely large H ii region, the Barnard’s Loop (BL)? The much more diffuse nebulae to the west (Fig. 1) are most likely due to BL. Heiles et al. (2000) find that in BL $n_e \sim 2.0 \text{ cm}^{-3}$, which is 1–2 orders of magnitude lower than the values of the nebulosities we have measured. If these arcs were related to BL, it would be a real problem for such diffuse nebulae to be locally enhanced into such well-defined structures. So it becomes highly possible that these arcs are HH shocks. In view of their rather low radial velocities ($V_{RHelio} \sim -20$ to $-40 \text{ km s}^{-1}$, or $V_{RLSR} \sim -5$ to $-25 \text{ km s}^{-1}$), more extended morphology features, and the narrow line width ($\Delta V_{FWZI} \sim 45.0 \text{ km s}^{-1}$), the bow shocks observed by us cannot be taken as normally defined HH objects. In addition, there is neither a YSO nor molecular dense gas near these shocks; these striking features could come from somewhere far away. Since the spatial extent that HH objects or jets are thought to flow through has been increased typically from 0.3 to 3 pc, and even then to 10 pc, we now have no reason to suspect that some HH objects could even pass through a larger scale. These nebulosities are possibly such a case.

As already intuitively suggested by Figure 1 and kinematically analyzed in \S 3.2 and 3.3, it turns out that these nebulosities lose velocity and excitation but gain size when moving southward, i.e., going south from nebulosity K to C. So the center of expansion is somewhere in the north. Inspecting the large-scale distribution of the giant bipolar HH flows investigated by Reipurth et al. (1998) and Mader et al. (1999), nebulosity C is aligned with HH 404, HH 403, and HH 127 (Fig. 10), which are on the direction with a position angle (P.A.) of 16°, while HH 131, HH 127, and the L1641-N VLA source are on a line with P.A. $\sim 11^\circ$. HH 404, HH 403, and HH 127 form a giant bipolar HH flow driven by L1641-N VLA (Reipurth et al. 1998). We wonder if nebulosity C is associated with the giant HH flow or not. If HH 131 and nebulosities C and L were driven by the VLA source, the distance that the bow shocks have moved through would be $d \sim 15$ pc, and the age of the shocks would be about $2 \times 10^5 \text{ yr}$, provided the average velocity of the shocks is $V \sim 100 \text{ km s}^{-1}$ when they flow through the ISM. However, the VLA source is a deeply embedded YSO and therefore unlikely

![Figure 9](image-url)
We have carried out echelle spectrographic observations toward two giant bow shocks (nebulosities Cw and L) associated with HH 131 in Orion using the HDS at the Subaru Telescope. With the low-dispersion spectrograph at the NAO 2.16 m telescope, spectra of nebulosities C, L, and K have been obtained. Position-velocity distributions of nebulosities Cw and L have been analyzed from the long-slit spectra observed with the HDS Hα narrowband filter. We summarize the conclusions as follows:

1. Strong [S II] λ6717, 6731, Hα, and [N II] λ6583 emission lines have been detected toward nebulosities C, Cw, L, and K. The electron densities of all the observed nebulosities are low ($n_e \sim 10^2$ cm$^{-3}$), which has been deduced from the line ratio of [S II] λ6717/6731. The excitation and electron density tend to decrease from K to L and C, so there is a tendency for the flow to become less excited and less ionized when going further to the south, where the most extended (and presumably evolved) objects are seen.

2. Double kinematic signatures have been found in nebulosity Cw from its [N II] λ6583 profiles. The observed Hα profiles of Cw are almost symmetric. Bow shock models agree with the observed position-velocity diagrams of [N II] to a higher degree than with Hα spectra, and a spatially resolved bow shock with its wing, apex, and postshock is likely revealed near Cw from the [N II] emission.

3. The fastest radial velocity of nebulosity Cw is $V_r \sim -18.0$ km s$^{-1}$. When the flow at L goes to the south, it slows down. The fastest radial velocity of L is $-45.0$ km s$^{-1}$, and the slowest value is about $-18.3$ km s$^{-1}$. The radial velocity gradient is about 200 km s$^{-1}$ pc$^{-1}$. The similarity of the fastest radial velocity of Cw to the slowest value of L and their spatial connection indicate that they are physically associated.

4. The high line ratio of [S II] λ6717 + 6731)/Hα and the nondetection of [O III] λ5007 suggest that nebulosities C, Cw, L, and K are characterized by low- to intermediate-excitation HH spectra.

5. No certain source has been assigned to drive these giant features. They might have been ejected out of the Orion A GMC; later on they continue expanding in the rather sparse ISM and preserve their morphology.

4. CONCLUSIONS

The authors wish to acknowledge the efforts and excellent support of the Subaru staff members during observations and especially thank Akito Tajitsu and Aoki Wako for their helpful discussions in the data reductions. We also acknowledge the staff members of the NAO 2.16 m telescope and the Beijing-Arizona-Taiwan-Connecticut (BATC) Beijing groups for their efforts and helpful support during the observations of this project. This research was supported by National Natural Science Foundation of China (NSFC) grants 10133020, 10243004, 10473022, and G19990754.

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