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HERBIG-HARO OBJECTS HH 434–436: PART OF A GIANT FLOW DRIVEN BY THE CENTRAL SOURCE A/B OF IRAS 04325+2402?

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ABSTRACT

While carrying out a wide-field survey of nearby star-forming regions for Herbig-Haro (HH) objects we discovered three Herbig-Haro objects, HH 434–436, in a $\sim 2' \times 2'$ (0.08 × 0.08 pc) region near L1536. HH 434 consists of three knots. HH 435 shows a bow shock shape, and HH 436 is an elongated patch. Spectroscopic observations indicate that the excitation levels of HH 434–436 are different: HH 436 has a high excitation level, while 434A has an intermediate, and 435 has a low excitation level. The overall morphology of HH 434–436 shows a bow shock shape and suggests that HH 434–436 may be a single bow shock fragmented into separate knots. Near-infrared observations of the region in the JHK' broad bands and H_2 $v = 1$–0 $S(1)$ narrow band were also carried out, but no embedded source was detected. The overall bow shock of HH 434–436 points back toward an embedded multiple system, IRAS 04325+2402. Moreover, from *Hubble Space Telescope* Near Infrared Camera and Multi-Object Spectrometer 3 observations HH 434–436 are located on the expected outflow axis of the central source A/B of this multiple system. On the basis of these facts we propose that HH 434–436 may be driven by the central source A/B of IRAS 04325+2402; therefore, they are probably part of a giant HH flow, which has a scale of 2.4 pc, although the possibility that HH 434–436 are three distinct flows cannot be completely ruled out.

Key words: ISM: Herbig-Haro objects — ISM: jets and outflows — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Protostars produce mass outflows along their polar axes while they are still accreting mass from the disks and envelopes that surround them. Herbig-Haro objects are small-scale shock regions intimately associated with star-forming regions.[5] Although mass outflows from young stellar objects (YSOs) have their demonstrations in the near-infrared and millimeter-wave bands such as molecular hydrogen emissions (e.g., McCaughrean, Rayner, & Zinnecker 1994) and CO outflows (e.g., Gueth & Guilloteau 1999), Herbig-Haro phenomena provide unique insights into the processes that lead to the formation of stars (Reipurth & Heathcote 1997). Particularly in the past few years more than two dozen parsec-scale giant HH flows have been found in the nearby star-forming regions (Bally & Devine 1994; Reipurth, Bally, & Devine 1997). These flows are up to 10 times longer than previously recognized HH flows and imply that mass loss from YSOs may profoundly affect the molecular cloud environment in active star formation regions and may play an important role in cloud dynamics.

We have carried out a wide-field survey of star-forming regions for Herbig-Haro objects to investigate the outflow activity of these regions (Yan et al. 1998; Zhao et al. 1999; Wang et al. 2000; Yang & Yao 2000). The HH objects discovered in our survey display various morphologies, such as knots, patches, bow shocks, jets, and complex structures. In this paper we report our discovery of three HH objects, HH 434–436, in the region near the dark cloud L1536. Low-dispersion spectroscopic observations were made toward HH 434A, 435, and 436. Near-infrared JHK' broadband and H_2 $v = 1$–0 $S(1)$ narrowband imaging was also made to search for embedded sources and associated H_2 emissions. Finally, a survey of nearby YSOs in the literature is made to identify the possible exciting sources of HH 434–436.

2. OBSERVATIONS AND DATA REDUCTION

The optical imaging was carried out at Xinglong Station of Beijing Astronomical Observatory (BAO). The telescope used is the f/3 60/90 cm Schmidt telescope equipped with a 2048 × 2048 Aerospace Ford CCD, which has a field of view of $57' \times 57'$. The pixel size is 15 μm, corresponding to a resolution of 1".67 pixel^{-1} (Fan et al. 1996). The discovery of HH 434–436 was made in our quick survey of HH objects on 1995 November 15 using two BATC[6] intermediate-band filters, [BATC09] ($\lambda_c = 6660$ Å, $\Delta\lambda = 480$ Å) and [BATC10] ($\lambda_c = 7050$ Å, $\Delta\lambda = 300$ Å) and was subsequently confirmed by narrowband [S II] filter ($\lambda_c = 6725$ Å, $\Delta\lambda = 50$ Å) observations on 1996 December 6. The [BATC09] filter well covers the strong and characteristic lines of HH objects, while the [BATC10] band covers no strong line of HH objects and therefore is used to measure the continuum. Three frames in each band of [BATC09], [BATC10], and [S II] were taken so that the cosmic rays and the bad pixels could be removed. The total exposures in [BATC09], [BATC10], and [S II] bands are 1440, 1440, and 3600 s, respectively. The seeing during the observations was typically $\sim 2''$. Bias subtraction, dome flat-field normalization, and image combination were conducted using the IRAF package.

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[5] See http://casa.colorado.edu/hhcat.

[6] BATC: Beijing Arizona Taiwan Connecticut Multicolor Sky Survey.

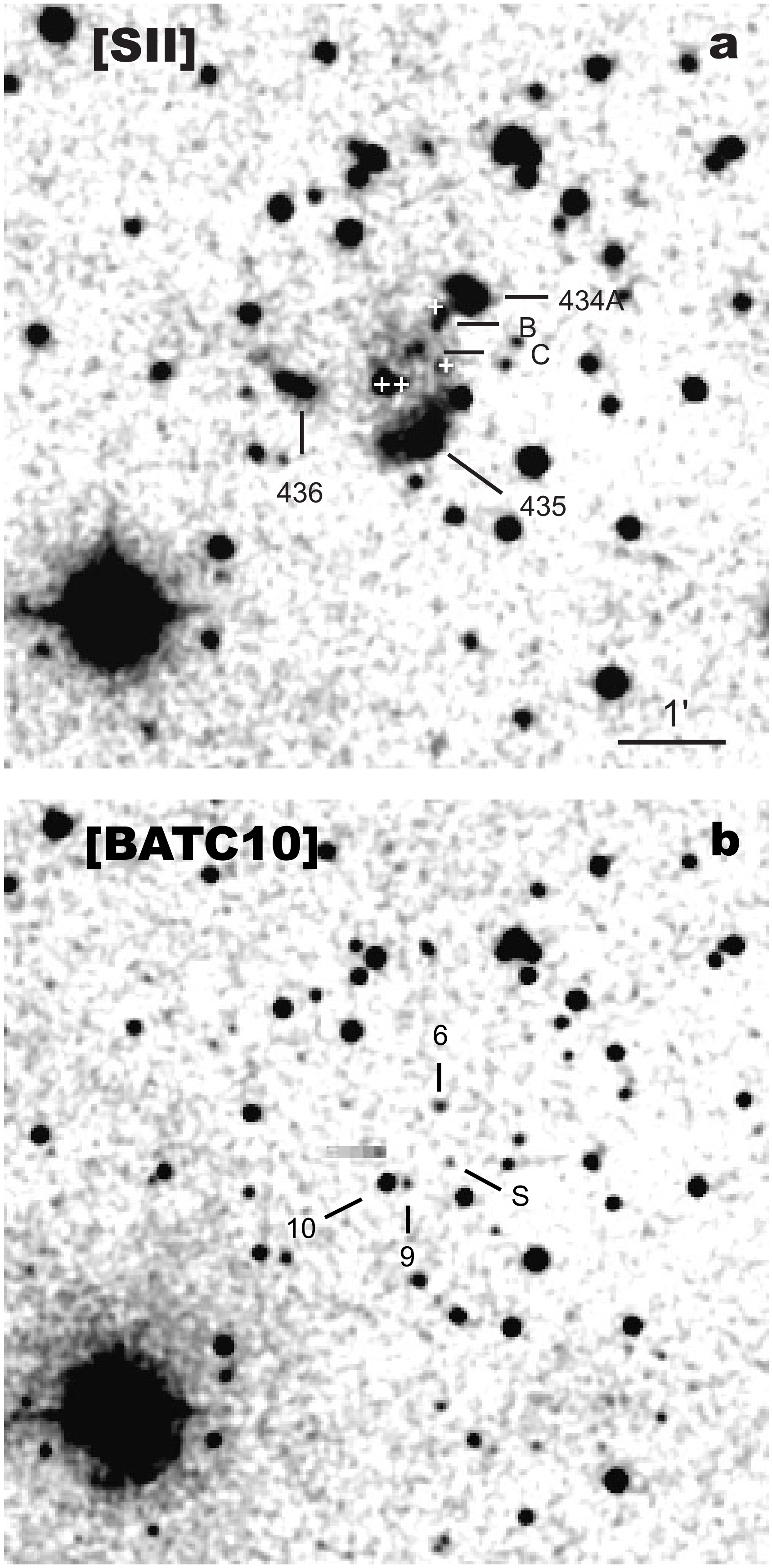


FIG. 1.—Images of HH 434–436 in (*a*) [S II] band and (b) [BATC10] band. Stars 6, 9, 10, and S from Table 2 are marked with plus signs in (*a*) and labeled in (*b*). All the fields are 7′ × 7′. North is up, east is to the left, and the scale is shown in (*a*).

Low-dispersion spectroscopic observations of HH 434A, 435, and 436 were made with the BAO 2.16 m reflector using a Cassegrain spectrograph during the period 1999 December 4–9. The grating used is 100 Å mm^{-1}, and the slit width is 1″.5. The resulting spectral resolution is $\sim$7 Å.

The near-infrared observations were carried out on 1999 November 18 at the 1.88 m telescope in Okayama Astronomical Observatory, Japan, using the infrared camera OASIS (Yamashita et al. 1995). OASIS, equipped with a near-infrared camera and multiobject spectrometer array (NICMOS3), provides a field of view of 4′.2 × 4′.2 with a resolution of 0″.97 pixel^{-1}. Five dithered J, H, K' (2.16 μm) and H_2 $v = 1$–0 $S(1)$ (2.12 μm) images were obtained, and the total exposures were 150, 50, 50, and 300 s, respectively. The weather conditions during the observations were good, and the seeing was around 2″.0. The images were dark-subtracted, flat field–normalized, sky frame–subtracted, registered, and combined using the IRAF package. The flat field was constructed with two sets of dome flat frames taken by switching an illuminating lamp on and off. The sky frame was obtained by median filtering the target images. The standard stars used are AS 08-0 and AS 08-2 (Hunt et al. 1998). The estimated uncertainties in our photometry are typically 0.1 mag. The 5 σ limiting magnitudes for the J, H, K' bands are 20.5, 18.8, and 18.3 mag pixel^{-1}, respectively.

3. RESULTS AND DISCUSSION

In Figure 1 we present the images of the newly found HH objects, HH 434–436, in [S II] and [BATC10] bands. The details of HH 434–436 could be seen more clearly in the contour map of the region (Fig. 2). The HH nature of HH 434–436 is apparent from the [S II] and [BATC10] images. The coordinates of HH 434–436 in the 1950 epoch are listed in Table 1. The astrometry is done by using the Guide Star Catalog (GSC).

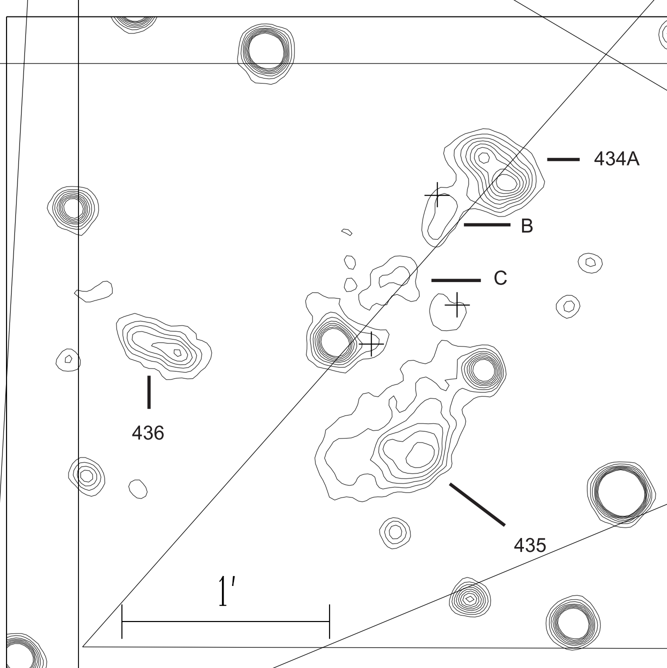
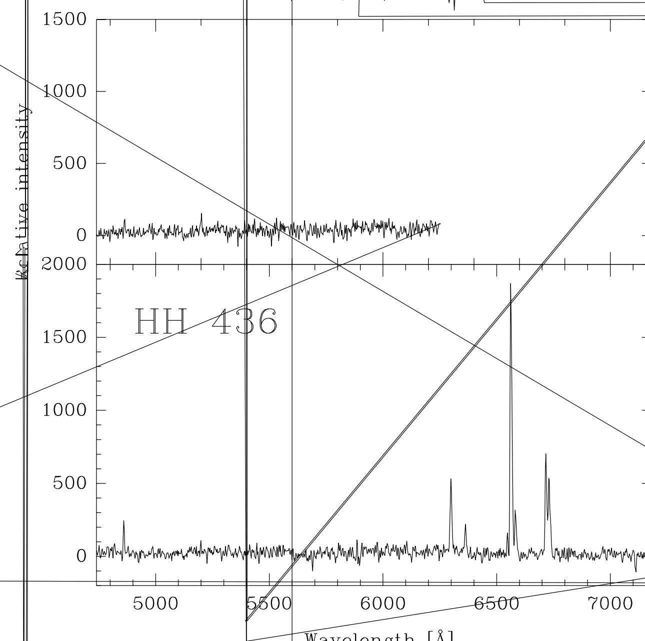


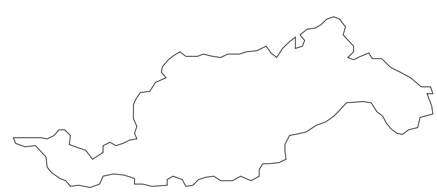
FIG. 2.—Contour map of the HH 434–436 region. The lowest level corresponds to 3 σ (the sky noise level), and the interval is 2 σ. Stars 6, 9, and S from Table 2 are marked with plus signs.

TABLE 1

NEW HERBIG-HARO OBJECTS

Object	α (1950)	δ (1950)	Comments
HH 434A......	4 31 12.99	23 03 16.2	Knot
HH 434B......	4 31 14.22	23 03 09.4	Knot
HH 434C......	4 31 15.26	23 02 47.1	Knot





(Whitney et al. 1997), $\theta_{neb} = 85°$ for IRAS 04302+2247 (Padgett et al. 1999), $\theta_{neb} = 18°$ for IRAS 04325+2402 (Whitney et al. 1997), and $\theta_p \approx 70°$ for each component of the IRAS 04328+2248 (HP Tau) triple system (Monin, Ménard, & Duchêne 1998). From these measurements the outflow axes can be derived by assuming that they are along the nebula symmetry axes and are perpendicular to the polarization vectors. The derived outflow axes are indicated by dotted lines in Figure 4.

IRAS 04325+2402 is in fact a multiple system. *HST*/NICMOS3 observations resolved IRAS 04325+2402 into a central source A/B and its companion, C, (Hartmann et al. 1999). Source A/B lies near the apex of the main bipolar reflection nebula, and source C is well separated from source A/B at a projected distance of 8''.2. The orientation of the main reflection nebula lies in the direction of P.A. $\approx 20°$ (see Fig. 2 of Hartmann et al. 1999). The position angle of the symmetry axis measured by Whitney et al. (1997) for the IRAS 04325+2402 infrared nebula, as illustrated in Figure 4, is consistent with the above orientation. The expected axis of an outflow from the central source A/B of IRAS 04325+2402 is along the orientation of the main reflection nebula. From Figure 4 one can see that HH 434–436 lie well on this expected outflow axis.

We note that the CO outflow at P.A. $\approx -45°$ (Heyer et al. 1987) in the IRAS 04325+2402 region is close to the orientation expected for an outflow from source C (see Fig. 7 of Hartmann et al. 1999) and completely inconsistent with the orientation of the main reflection nebula. This CO outflow should have no relationship to HH 434–436.

In summary, our *JHK'* photometry suggests that HH 434–436 are probably not excited by nearby sources. The overall bow shock of HH 434–436 shows a symmetry axis of P.A. $\approx 25°$ that points toward IRAS 04325+2402. Furthermore, HH 434–436 lie on the expected axis of an outflow from the central source A/B of IRAS 04325+2402. On the basis of these facts we suggest that HH 434–436 are probably driven by the central source A/B of IRAS 04325+2402. The angular distance between HH 434–436 and the central source A/B of IRAS 04325+2402 is 1°.0, which corresponds to a scale of 2.4 pc. Therefore, besides HH 300/300D and HH 410/411, HH 434–436 are probably another giant HH flow in the southeastern part of the Taurus complex.

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