Wide Field Surveys of Herbig-Haro Objects

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ABSTRACT

We report our new results from wide-field surveys of Herbig-Haro (HH) objects in the nearby star forming regions. The surveys covered approximately 56 deg² in Perseus, Taurus, Orion, Monoceros, and other regions. Using refined techniques, we discovered in total 68 HH objects, of which 32 were in Perseus, 4 in Taurus, 13 in Orion, 18 in Monoceros, and 1 in S287 regions. The newly discovered HH objects demonstrate a great variety of morphological structures, including 5 jets, 7 arcs, 12 cirri or cirrus groups, 13 patches, and many knots. These objects provide a new comprehensive database for the study of HH objects in the regions of recent star formation.

1. Introduction

Herbig-Haro (HH) objects are small shock-excited nebulae intimately associated with star forming regions (see reviews by Schwartz 1983 and Raga 1989). Like high velocity CO molecular outflows and shock-excited near-IR emissions of H₂, HH objects are good tracers of the mass outflow activities of young stellar objects (YSOs) and can be used to trace the extremely young class 0 objects embedded in dense molecular cores – about 30% class 0 objects are now known to be associated with HH objects (Eiroa et al 1994).

The prototype HH objects, HH 1 and 2, were discovered by Herbig (1951) and Haro (1952) in their Hα emission star survey. Since then about 300 HH objects have been found by several searching methods, including objective-prism Schmidt survey, narrow-band CCD imaging, near-IR imaging, and other methods (Reipurth 1994).

In this paper, we describe the way of our large-field CCD Schmidt surveys of HH objects using intermediate band filters, and report the discovery of a large number of new HH objects in Perseus, Taurus, Orion, Monoceros, and other star forming regions.

2. Observations and Identification Techniques

2.1. Instrumentation and Filters

The observations of the surveys were carried out at Xinglong Station of Beijing Astronomical Observatory (BAO) during the winters of 1995-1997. The telescope used is the BAO f/3 60/90cm
Schmidt telescope equipped with a 2k×2k Aerospace Ford CCD which has a pixel size of 15µ, corresponding to a resolution of 1.67"/pixel, and has a total field of view of 58'. On average, the seeing at the site is around 2". The filter set used in this program are two BATC intermediate band filters [BATC09], [BATC10], and a narrow band filter [BATC26]. The parameters of the filters are given in Table 1. As shown in this table, the [BATC09] filter well covers the strong and characteristic lines of HH objects, while the [BATC10] band has no strong lines of these objects and, therefore, can be used to represent the continuum.

Table 1: Filter Parameters

| Filter ID | Central Wavelength | Band Width | Property |
|-----------|--------------------|------------|----------|
| [BATC09]  | 6660 Å             | 480 Å      | [NII], Hα, [SII] |
| [BATC10]  | 7050 Å             | 300 Å      | Continuum |
| [BATC26]  | 6725 Å             | 50 Å       | [SII] λ6717/6731 |

2.2. Field Selection

HH objects are produced by interactions of mass outflows of YSOs with the surrounding medium (Schwartz 1975). They are associated with other tracers of the activities of YSOs, such as molecular outflows, H2O or OH masers, and they usually occurs in groups. For the purpose of large field surveys of HH objects in star forming regions, we have selected 56 fields in the surveys based on the following selection criteria:

1. There are known HH objects, molecular outflows, H2O or OH masers in or near the field;
2. There are IRAS sources of class 0 or class 1, VLA continuum emissions in the field;
3. There are GGD or RNO objects in the field.

Table 2 gives the log of the surveys.

2.3. Identification Techniques

Our survey sequence includes a first-step quick survey for HH candidates (Runs A and B in Table 2) and a narrow-band identification (Runs C and D). The subsequent observations of this survey program is in progress, and the details of each target field will be reported in a later paper.

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1BATC-Beijing-Arizona-Taiwan-Connneticut Multicolor Sky Survey
Table 2: Log of observations

| Field id | R.A.  | DEC  | BATC09(min.) | BATC10(min.) | Run* | BATC26(min.) | Run* |
|----------|-------|------|--------------|--------------|------|--------------|------|
| A01      | 03:21:30 | 30:10:00 | 15          | 15          | A    |              |      |
| A02      | 03:25:30 | 30:10:00 | 15          | 15          | A    | 60          | C    |
| A03      | 03:29:30 | 30:10:00 | 15          | 15          | A    | 60          | C    |
| A04      | 03:31:30 | 31:00:00 | 15          | 15          | A    |              |      |
| A05      | 03:25:30 | 31:00:00 | 15          | 15          | A    | 60          | C    |
| A06      | 03:29:30 | 31:00:00 | 15          | 15          | A    | 60          | C    |
| A07      | 03:41:20 | 31:25:00 | 15          | 15          | A    |              |      |
| A08      | 03:45:20 | 31:25:00 | 20          | 18          | A    |              |      |
| A09      | 03:41:20 | 32:15:00 | 15          | 15          | A    |              |      |
| A10      | 03:45:20 | 32:15:00 | 15          | 15          | A    | 60          | C    |
| A11      | 04:24:27 | 26:00:00 | 20          | 20          | A    |              |      |
| A12      | 04:31:17 | 22:50:00 | 24          | 24          | A    | 60          | C    |
| A13      | 04:01:41 | 26:00:00 | 20          | 20          | A    |              |      |
| A14      | 04:35:20 | 25:18:00 | 15          | 20          | A    |              |      |
| A15      | 04:32:00 | 24:18:00 | 15          | 15          | A    |              |      |
| A16      | 04:28:00 | 24:18:00 | 15          | 15          | A    |              |      |
| A17      | 04:15:20 | 28:00:00 | 15          | 15          | A    |              |      |
| A18      | 04:17:00 | 27:03:00 | 15          | 15          | A    |              |      |
| A19      | 04:19:04 | 19:25:00 | 15          | 15          | A    |              |      |
| B01      | 05:48:40 | 01:55:00 | 20          | 20          | B    |              |      |
| B02      | 05:48:40 | 02:50:00 | 20          | 20          | B    | 60          | C    |
| B03      | 05:52:20 | 01:55:00 | 20          | 20          | B    |              |      |
| B04      | 05:52:20 | 02:50:00 | 20          | 20          | B    | 60          | D    |
| B05      | 06:06:00 | 06:20:00 | 24          | 24          | B    | 60          | C    |
| B06      | 06:09:40 | 06:20:00 | 24          | 24          | B    |              |      |
| B07      | 06:27:17 | 22:50:00 | 24          | 24          | B    |              |      |
| B08      | 06:35:17 | 22:50:00 | 24          | 24          | B    |              |      |
| B09      | 06:57:30 | 04:35:00 | 24          | 24          | B    | 60          | D    |
| B10      | 06:57:17 | 07:42:16 | 6           | 24          | B    |              |      |
| B11      | 06:33:20 | 30:35:00 | 20          | 20          | B    |              |      |
| B12      | 07:03:45 | -11:15:00 | 20          | 20          | B    |              |      |
| B13      | 06:38:20 | 10:35:00 | 20          | 20          | B    | 60          | D    |
| B14      | 03:33:20 | 31:25:00 | 20          | 20          | B    |              |      |
| B15      | 03:37:20 | 30:35:00 | 20          | 20          | B    |              |      |
| B16      | 06:38:20 | 09:40:00 | 20          | 20          | B    | 60          | D    |
| B17      | 06:05:46 | 21:35:00 | 20          | 20          | B    |              |      |
| B18      | 03:37:20 | 31:25:00 | 20          | 20          | B    |              |      |
| B19      | 03:37:20 | 32:15:00 | 20          | 20          | B    |              |      |
| B20      | 03:41:20 | 30:35:00 | 20          | 20          | B    |              |      |
| B21      | 06:06:00 | 18:00:00 | 20          | 20          | B    |              |      |
| B22      | 06:59:50 | 18:00:00 | 20          | 20          | B    |              |      |
| B23      | 03:03:32 | 58:19:00 | 20          | 20          | B    |              |      |
| B24      | 03:23:00 | 58:36:00 | 20          | 20          | B    |              |      |
| B25      | 06:11:48 | 13:51:00 | 20          | 20          | B    | 60          | D    |
| B26      | 03:45:20 | 33:05:00 | 20          | 20          | B    |              |      |
| B27      | 06:56:46 | 03:53:00 | 20          | 20          | B    |              |      |
| B28      | 06:45:20 | 02:09:30 | 20          | 20          | B    |              |      |
| B29      | 06:36:30 | 08:50:00 | 20          | 20          | B    |              |      |
| B30      | 06:31:00 | 04:10:00 | 20          | 20          | B    |              |      |
| B31      | 05:59:00 | 16:15:00 | 20          | 20          | B    |              |      |
| B32      | 05:36:00 | 35:55:00 | 20          | 20          | B    |              |      |
| B33      | 05:34:30 | 31:58:00 | 20          | 20          | B    |              |      |
| B34      | 05:44:00 | 09:50:00 | 20          | 20          | B    |              |      |
| B35      | 05:44:00 | 09:50:00 | 20          | 20          | B    | 60          | D    |
| B36      | 05:44:00 | 09:50:00 | 20          | 20          | B    | 60          | D    |
| B37      | 05:40:20 | 01:44:00 | 20          | 20          | B    | 60          | D    |

(*) Run code: A-Oct 15,1995∼Dec 20,1995; B-Feb 13,1996∼Mar 18,1996; C-Dec 6,1996∼Dec 9,1996; D-Mar 7,1997∼Mar 11,1997
Here we give the techniques of picking up new HH objects and some snapshots of our first results. For a target field, 3 or more frames in both [BATC09] and [BATC10] bands were taken and combined so that the cosmic rays and the bad pixels were eliminated in the resultant images. The two resultant frames in [BATC09] and [BATC10] bands were blinked and compared. Due to their strong emissions in \( \text{H}_\alpha \), [NII] and [SII] lines, HH objects are prominent in [BATC09] band but usually invisible in [BATC10] band because of their very low continuum emission in this passband. HH candidates were picked up from the careful comparison between the two images. The minimum angular size of detectable candidates is limited by the pixel size and is about 2\( '' \) in our surveys. In this step we picked up about 150 HH candidates in the 56 fields.

In the first step there is some possibility of contamination by compact HII regions and reflection nebulae. Our second step is to identify the candidates using the narrow-band [BATC26] filter, which covers two characteristic lines of HH object, \( \lambda \lambda 6717, 6731 \). We have made this further identification in 15 fields out of the 56 target fields in table 2. Three frames, each with an exposure time of 20 minutes, were taken; Then the frames were reduced just as in the [BATC09] and [BATC10] bands. We found that above 90 percent of the candidates of HH objects from our first step are identifiable in the [BATC26] band. The images of HH objects are sharper in the [BATC26] frames than in the [BATC09] frames. In contrast, the compact HII regions and reflection nebulae are invisible in the [BATC26] frames.

In order to demonstrate the effectiveness of our surveys, we present in Figure 1 four sample fields out of the long list of Table 3. For each field, we give 3 images taken with our filter set in a row of the image array of Figure 1. The first column is the narrow band [BATC26] images, the second and third columns are [BATC10] and [BATC09] band images, respectively. The HH objects detected in both [BATC26] and [BATC09] bands are marked using the numbers assigned in our surveys. In all the fields, HH objects show up only in [BATC09] and [BATC26] bands, with their images more prominent in [BATC26], whereas they are completely invisible in [BATC09] band. The first field, labeled A02 in the top row, has dimensions of 512\( \times \)512 pixels, in which the HH objects 1A, 1B, 1C and 4, 5 are coincident, respectively, with HH279C, HH279B, HH279A and HH317, HH318 in Bally et al.’s list (Bally et al. 1996, 1997), therefore this field may also serve as a comparison of our observations with theirs. Comparing with their work, it is clear that all the HH objects falling into the region overlaped with Bally et al.’s (1997) were picked up using our method. The rest rows are 3 other HH object survey fields: A06, A10, and A12, whose sizes are, respectively, 200\( \times \)200, 300\( \times \)300 and 200\( \times \)200 in pixels. A02 is located in L1455, A12 is in the vicinity of CI Tau, and A06 is located at about 1\( ^{\circ} \)east of NGC1333.

### 3. Results and Discussion

From the 56 target fields, we discovered more than 150 HH candidates by comparison between [BATC09] and [BATC10] frames. From the 15 [BATC26] fields, we identified 68 new HH objects. These objects are listed in Table 3. In the table, column 1 is the numbers of the newly detected
Fig. 1.— The [BATC26], [BATC10], and [BATC09] band images of 4 sample fields of our surveys, each row corresponds to a field. For details see text.
HH objects assigned in our surveys, columns 2 and 3 are, respectively, the right ascension and declination in 1950 epoch. The source positions were derived using the Guide Star Catalog. The overall accuracy is estimated to be about 0.5 arcsec (Fan et al. 1996). A brief comment to each object is given in column 4. Among the 68 objects, 15 objects coincide with those reported by Bally, Devine, & Reipurth (1996) and Bally et al. (1997). These objects are all in the fields A02 and A05, which are the central part of NGC 1333 in Perseus.

According to their morphological properties, the new HH objects are classified into knots, jets, arcs, patches, and cirri. Most of the 68 new HH objects are either bright or faint knots, while a few of them are cirri or cirrus groups, arcs, and jets. There are 7 HH objects showing arc structures, including No.1A, 7, 8, 11, 60, 62 and 63. Objects No.1, 9, 31, 34, and 56 are remarkable in that they show extended jets. HH No.1A, which is coincident with HH 279C in Bally et al. (1997), extends to No.1C (HH279A in Bally et al. 1997) forming a large jet structure, as clearly shown in the top row of Fig 1. HH objects No.31A and 31B are two main knots of a spectacular jet in the field A10, which is located at about 2° east of Barnard 5. It is also possible that the jet-like HH flows of HH No.31A, 31B, and 31C are the northern part of a bow structure with the apex at HH No.31A. We note that about one third of the newly discovered HH objects occur in groups. By the term “occur in group” we mean that in the vicinity of 0.5 pc from a HH object there is at least one other HH object.

For the local star forming regions, where the fields are rarely contaminated by the compact HII regions, We believe that the filter combination of [BATC09] and [BATC10] is an efficient and reliable procedure to find new HH objects.

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Table 3: A List of New Herbig-Haro Objects

| PMO No. | RA (1950) | DEC (1950) | Comments |
|---------|-----------|------------|----------|
| 1A      | 3:24:14.56 | 30:09:59.5 | arc (HH279C)* |
| 1B      | 3:23:54.97 | 30:08:13.7 | jet (HH279B)* |
| 1C      | 3:23:53.59 | 30:09:09.4 | cirrus (HH279A)* |
| 2       | 3:23:55.03 | 31:25:41.2 | bright knot with star |
| 3       | 3:23:55.42 | 30:15:31.1 | knot (HH278)* |
| 4       | 3:24:07.40 | 30:01:29.1 | cirrus (HH317)* |
| 5       | 3:24:40.65 | 30:03:53.3 | knot (HH318)* |
| 6A      | 3:25:07.45 | 31:09:21.8 | knot (HH338A)* |
| 6B      | 3:25:06.12 | 31:07:52.6 | cirrus (HH338C)* |
| 7       | 3:25:10.03 | 30:39:36.3 | arc (HH351)* |
| 8       | 3:25:44.91 | 30:59:17.6 | arc (HH341)* |
| 9A      | 3:25:48.99 | 30:55:02.2 | knot (HH343A)* |
| 9B      | 3:25:46.55 | 30:55:23.5 | jet (HH343D)* |
| 10      | 3:25:49.30 | 30:42:06.9 | two knots |
| 11      | 3:25:49.44 | 30:54:24.0 | arc (HH350)* |
| 12A     | 3:25:55.40 | 31:02:55.9 | knot (HH344A)* |
| 12B     | 3:25:53.98 | 31:01:57.1 | knot (HH344B)* |
| 13A     | 3:26:10.15 | 31:05:04.9 | knot (HH347B)* |
| 13B     | 3:26:11.59 | 31:05:07.4 | knot (HH347A)* |
| 14      | 3:26:12.64 | 30:49:33.6 | knot (HH352)* |
| 15      | 3:26:21.76 | 31:03:16.6 | cirrus (HH348)* |
| 16A     | 3:26:32.79 | 31:20:02.5 | patch (HH353)* |
| 16B     | 3:26:28.14 | 31:19:56.1 | cirrus |
| 17      | 3:26:30.68 | 31:03:17.2 | cirrus (HH349)* |
| 18      | 3:27:28.59 | 30:17:36.7 | comma-like knot |
| 19      | 3:27:33.11 | 30:41:44.4 | knot |
| 20      | 3:27:40.89 | 30:19:11.1 | knot |
| 21      | 3:27:42.39 | 30:27:50.9 | knot |
| 22      | 3:27:48.56 | 30:14:26.1 | faint patch |
| 23A     | 3:27:52.26 | 30:24:40.0 | faint patch |
| 23B     | 3:27:55.29 | 30:25:07.6 | faint patch |
| 24      | 3:28:42.35 | 30:59:50.3 | bright knot |
| 25      | 3:28:45.84 | 30:59:43.5 | bright knot |
| 26      | 3:29:21.71 | 31:14:31.8 | faint patch |
| 27      | 3:29:58.81 | 31:16:12.7 | bright knot with faint cirrus |
| 28      | 3:30:09.16 | 30:59:03.5 | knot |
| 29A     | 3:30:27.49 | 30:59:40.8 | knot |
| 29B     | 3:30:29.77 | 30:58:47.3 | group of knots |
| 30A     | 3:30:43.72 | 30:54:54.5 | knot with cirrus |
| 30B     | 3:30:44.37 | 30:54:58.3 | knot |
| 30C     | 3:30:44.48 | 30:55:01.3 | knot |
| 30D     | 3:30:45.03 | 30:55:20.1 | knotendar (HH380SE part of the jet) |
| 31A     | 3:43:49.77 | 32:36:03.8 | bright knot, SE part of the jet |
| 31B     | 3:43:53.81 | 32:37:06.9 | knot, middle part of the jet |
| 31C     | 3:43:58.57 | 32:37:58.8 | patch, NW part of the jet |
| 32      | 3:43:56.54 | 32:33:47.2 | several faint knots |
| 33      | 4:30:12.46 | 22:48:51.8 | knot |
| 34A     | 4:31:12.99 | 23:03:16.2 | bright knot |
| 34B     | 4:31:14.22 | 23:03:09.4 | knot, middle part of jet |
| 34C     | 4:31:15.26 | 23:02:47.1 | knot, middle part of jet |
| 35      | 4:31:14.90 | 23:01:55.7 | bright knot |
| No | RA. (1950) | DEC. (1950) | Comments |
|----|-----------|------------|----------|
| 36 | 4:31:20.15 | 21:02:28.0 | bright knot |
| 37A | 5:39:14.36 | -1:46:28.1 | bright knot |
| 37B | 5:39:11.50 | -1:47:52.8 | bright knot |
| 38 | 5:44:02.11 | 0:24:59.0 | knot with cirrus |
| 39 | 5:44:07.94 | 0:24:34.2 | knot |
| 40 | 5:44:31.73 | 0:20:45.7 | bright knot |
| 41A | 5:44:33.49 | 0:10:45.5 | knot |
| 41B | 5:44:36.90 | 0:09:58.4 | knot |
| 41C | 5:44:38.39 | 0:09:59.5 | knot |
| 42 | 5:44:33.96 | 0:23:51.8 | faint knot |
| 43A | 5:45:33.12 | 0:17:58.3 | knot |
| 43B | 5:45:30.00 | 0:18:14.7 | diffuse faint patch |
| 44A | 5:45:45.02 | 0:24:46.3 | knot |
| 44B | 5:45:44.13 | 0:24:39.4 | faint knot |
| 45 | 5:47:35.85 | 2:52:14.9 | 2' diameter complex |
| 46 | 5:48:31.27 | 2:41:06.9 | knot |
| 47 | 5:49:26.63 | 3:01:33.0 | knot |
| 48 | 5:50:55.10 | 2:40:58.7 | knot |
| 49 | 5:51:33.01 | 2:36:37.7 | knot |
| 50A | 6:04:27.85 | -5:53:62.0 | faint knot |
| 50B | 6:04:27.28 | -5:54:05.1 | faint knot |
| 51A | 6:13:03.15 | 14:18:51.8 | bright arc-like knot |
| 51B | 6:13:05.50 | 14:18:22.7 | knot |
| 51C | 6:13:07.32 | 14:17:25.6 | knot |
| 51D | 6:13:07.91 | 14:17:56.3 | knot |
| 52A | 6:37:02.24 | 10:08:50.9 | knot |
| 52B | 6:37:00.58 | 10:09:21.6 | curved chain |
| 52C | 6:37:03.47 | 10:09:38.7 | cirrus |
| 52D | 6:36:50.59 | 10:10:01.6 | cirrus |
| 53 | 6:37:33.83 | 10:21:36.2 | bright complex |
| 54 | 6:37:45.51 | 9:56:16.5 | knot with diffuse patches |
| 55 | 6:37:46.25 | 10:10:47.0 | knot |
| 56 | 6:37:48.39 | 10:12:46.5 | chained knots or jet |
| 57A | 6:37:50.44 | 10:42:42.3 | bright knot |
| 57B | 6:38:02.18 | 10:41:26.3 | bright patch |
| 57C | 6:38:11.99 | 10:38:53.9 | patch |
| 57D | 6:38:24.57 | 10:38:39.7 | patch |
| 57E | 6:38:37.43 | 10:42:27.9 | knot with cirrus |
| 58A | 6:37:54.97 | 10:14:57.6 | knot aligned with 58B,58C |
| 58B | 6:37:55.64 | 10:15:17.2 | knot |
| 58C | 6:37:55.85 | 10:15:36.5 | knot |
| 59 | 6:37:59.95 | 9:35:42.4 | knot |
| 60 | 6:38:01.08 | 10:08:10.4 | arc |
| 61A | 6:38:09.89 | 10:09:34.1 | bright knot |
| 61B | 6:38:08.54 | 10:09:11.7 | bright knot |
| 62 | 6:38:13.75 | 10:16:41.1 | 5' bright arc |
| 63 | 6:38:13.76 | 9:35:48.8 | arc |
| 64A | 6:38:27.30 | 9:32:16.1 | bright patch |
| 64B | 6:38:31.04 | 9:32:03.1 | bright patch |
| 65 | 6:38:37.15 | 9:33:34.2 | bright patch |
| 66 | 6:38:38.54 | 9:30:55.5 | bright knot |
| 67 | 6:38:42.36 | 10:26:41.3 | 1' diameter complex |
| 68 | 6:57:11.21 | -4:46:54.2 | two knots |

(*) Detected also by Bally, et al. (1996, 1997)