New Herbig-Haro objects and outflows in Mon R1 association

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ABSTRACT

We present results of the narrow-band Hα and [S ii] imaging survey of Mon R1 association, performed with the 1 m Schmidt telescope of the Byurakan Observatory. Our observations covered one degree field near the center of the association. As a result of this study twenty new Herbig-Haro knots were discovered, some of which form collimated outflows. Among the most extended ones are HH 120 3 and HH 1196, which have a length near one parsec or even more.

In the course of search for the probable sources of HH objects several new small reflection nebulae were found. A list of all nebulous stellar objects in the Mon R1 area under study is presented, with the detailed description of most interesting objects. The near infrared data from the GLIMPSE360 and WISE surveys allowed to find several more objects, related to Mon R1, some of them with optical counterparts, as well as to outline at least three probable H2 collimated flows from the deeply embedded pre-main-sequence objects.

Key words: open clusters and associations: individual: Mon R1, stars: pre-main-sequence; ISM: jets and outflows, Herbig-Haro objects

1 INTRODUCTION

Herbig-Haro objects for a long time have been recognised as a sign of high activity of star formation in molecular clouds. In fact they represent shocked excitation zones where supersonic flows from young stellar objects (YSO) collide with interstellar medium and form small cloudlets with pure emission spectrum including permitted and low excitation forbidden emission lines ([O i], [S ii] etc). Thus, the discovering of new HH objects is important as for the further studies of the phenomenon of directed outflows from young stars, as well as for the searches for new star forming regions and groups.

On the other hand, it is well known that the sources of directed outflows with low and middle mass usually are associated with compact reflecting nebulae of characteristic conical shape. Moreover, further deep images in the optical and infrared ranges reveal their bipolar nature. Such shape is a consequence of the presence of circumstellar disks and conical cavities, created by matter outflow, near the YSOs illuminating these nebulae. In the overwhelming majority of cases HH objects and HH flows are located along the axes of the these cometary nebulae, which proves a direct relationship between all these phenomena.

We continue our searches for HH objects in the dark clouds, started in Byurakan observatory more than twenty years ago, with the new equipment and wider-field telescope (see sec. 2). Among the first targets we included in our program the Mon R1 association (Racine 1968).

This group of the stars, illuminating several bright reflection nebulae of various sizes, is located to the northwest from the famous Mon OB1 association. Some of them, e.g. NGC 2245 and NGC 2247, are well-known and studied by many authors. In general, Mon R1 contains at least about 30 young stellar objects (YSOs), found in optical range (Herbst et al. 1982). The distance of Mon R1 usually is assumed to be 800 pc, same as for nearby Mon OB1 (see Dahm 2003, for detailed review). One can see that YSOs in Mon R1 are spatially divided into two groups; one includes NGC 2245, NGC 2247 and IC 446, and another one is projected on the large reflection nebula IC 2169.

In contrast with adjacent Mon OB1, Mon R1 received much lower attention. Nearly all observational studies were concentrated on IC 446, where a compact group of emission-line stars, including HαBe star VY Mon, was...
found by Cohen & Kuhi (1979). Further observations in the infrared range confirmed an existence of the small cluster of probable YSOs around VY Mon (Wang & Looney 2007; Gutermuth et al. 2009, and references therein). No searches of HH objects in the Mon R1 field were performed so far.

Our field includes three brightest nebulae NGC 2245, NGC 2247 and IC 446, thus making our target the core of Mon R1 association.

2 OBSERVATIONS

Images were obtained on the nights of Feb. 3–4 2019 with 1m Schmidt telescope of Byurakan observatory, which was upgraded during 2013–2015 and equipped with CCD detector. Reworked 4K×4K Apogee (USA) liquid-cooled CCD camera was used as a detector with a pixel size of 0.868′′ and field of view of about 1 square degree (Dodonov et al. 2017).

Narrow-band filters centered on 6560 Å and 6760 Å, both with a FWHM of 100 Å, were used to obtain Hα and [S ii] images, respectively. A midband filter, centered on 7500 Å with a FWHM of 250 Å, was used for continuum imaging.

A dithered set of 5 min exposures was obtained in each filter. Effective exposure time in Hα equaled 6000 sec, in [S ii] – 7200 sec and in continuum – 2400 sec. Images were reduced in the standard manner using IDL package developed by one of authors (SND), which includes bias subtraction, cosmic ray removal, and flat fielding using “superflat field”, constructed by several images.

3 RESULTS

3.1 HH objects and flows

A Hα+[S ii] image, which is covering one square degree field of the Mon R1 region, is shown on Fig.1. The area includes three bright reflection nebulae (NGC 2245, NGC 2247 and IC 446), as well as several isolated dark lanes and emission-reflection stripes, which are stretched in SE-NW direction through the whole field. The zones with newly discovered HH objects and HH flows are marked by rectangles and are described individually. All found HH objects are listed in Table 1 in order of their right ascension. Besides, the Mon R1
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Table 1. The coordinates of HH objects and HH flows in the Mon R1 field.

| Name    | RA(2000) | Decl.(2000) | Notes                                           |
|---------|----------|-------------|------------------------------------------------|
| HH 1203A | 06 30 26.8 | +10 14 49    | Collimated HH object, associated with a cometary nebula |
| HH 1203B | 06 30 25.4 | +10 14 50    |                                                |
| HH 1203C | 06 30 24.7 | +10 15 11    |                                                |
| HH 1203D | 06 30 24.0 | +10 15 17    |                                                |
| HH 1202A | 06 31 12.8 | +10 25 35    | HH objects in the VY Mon region                |
| HH 1202B | 06 31 09.0 | +10 27 03    |                                                |
| HH 1202C | 06 31 08.3 | +10 26 26    |                                                |
| HH 1201A | 06 31 32.5 | +10 34 22    | A pair of HH knots about 2’ north from the LkHα 342 |
| HH 1201B | 06 31 32.5 | +10 34 01    |                                                |
| HH 1198A | 06 32 02.4 | +10 23 13    | An isolated group of HH knots                  |
| HH 1198B | 06 31 57.8 | +10 23 07    |                                                |
| HH 1198C | 06 31 56.9 | +10 22 39    |                                                |
| HH 1198D | 06 31 54.2 | +10 23 09    |                                                |
| HH 1197  | 06 31 58.8 | +10 27 45    | Compact HH object near RNO 72                  |
| HH 1196A | 06 32 30.9 | +10 17 48    |                                                |
| HH 1196B | 06 32 32.3 | +10 16 58    |                                                |
| HH 1196C | 06 32 35.1 | +10 16 22    |                                                |
| HH 1196D | 06 32 35.9 | +10 16 04    |                                                |
| HH 1196E | 06 32 36.2 | +10 15 43    |                                                |
| HH 1196F | 06 32 37.9 | +10 13 56    |                                                |

The association contains several nebulous stars. As they also can become the targets for the further investigations, we list and discuss them separately.

3.1.1 HH 1203 flow

This HH object includes four knots embedded in the diffuse emission (marked in Fig. 2 as A, B, C and D), representing the chain of HH objects. Brightest knot (B) in this chain is somewhat displaced from the axis of whole complex.

To the south-east from this HH group there is a compact cone-shaped reflection nebula, which lies on the axis of this elongated group. Just near the apex of this reflection nebula there is a very bright infrared source (IRAS 06277+1016; 2MASS J06302857+1014236). Apparently, just this infrared object represents the source of the collimated HH 1203 flow.

On Fig. 3 the continual image of this reflection nebula with overlapped [S ii] image is presented. This combination reveals the short emission jet, elongated in the direction of the axis of HH 1203 flow. Its existence confirms the assumption that the star, embedded into the nebula, is the source of HH 1203.

3.1.2 HH objects in the area of IC 446 and VY Mon

Reflection nebula IC 446 is located near the center of Mon R1 association, on the edge of a small dark cloud. As was mentioned above, it is surrounded by a cluster of emission-line and infrared stars, with dominating YSO VY Mon (Casey & Harper 1990).

We discovered three HH objects in this area (Fig. 4). The brightest one (HH 1202C) is located about 30’ north-east from VY Mon and is visible even on DSS-2 red images. This object has comparatively equal brightness in [S ii] and Ho. The second knot (HH 1202B) was detected in [S ii] images and is not visible in Ho. It is located in ≈12” to south-east from a close pair of stars, which are listed as 2MASS sources 06310840+1027111 and 06310815+1027109. The third one (HH 1202A) was found near the edge of dark nebula in ≈100” to the east from VY Mon. This HH object is visible only in Ho image.

It is naturally to expect that VY Mon, being the most luminous YSO in this field, can be a probable outflow source. Considering this it should be noted that the line, connecting HH 1202B and HH 1202C, passes near VY Mon. Moreover, a faint cone-shaped reflection nebula with the axis oriented toward these two HH objects, can be traced near this very active star.

The source of HH 1202A is not so obvious, but, probably, it can be associated with one of YSOs belonging to the cluster around IC 446.

3.1.3 HH 1201

To the north-east from IC 446 a pair of HH objects was discovered. This group is elongated in north-south direction; knots are separated by about 20’ (Fig. 5). This object was detected in Ho and is barely visible in [S ii]. To the south from these objects young star LkHα 342 associated with small optical reflection nebula can be found. This star is visible in 2MASS and WISE surveys, but it is not a prominent infrared source. The line, drawn along the oblong knot HH 1201 A, approximately is directed toward LkHα 342; however, this does not exclude other possible candidates for HH 1201 source.
3.1.4 HH 1198

This HH group consists of four knots and is extended in east-west direction, with total length of about 2′ (Fig. 6). Knots A, B and D are located on the same line; knot C is somewhat aside and is connected with B and D by narrow filaments. As whole, the morphology of this group is vague and resembles a heavily disrupted working surface of a flow, which source can be faraway in the uncertain direction.

3.1.5 HH 1197

This compact HH object (Fig. 7) is located near the small reflection nebula (RNO 72, HHL 43A), which will be discussed in the next section. This object is visible mainly in [S ii] and is very faint in Hα, which is typical for HH jets; however, its traces also can be found in the continuum image. An infrared 2MASS source J06315870+1027474 (also IRAS 06292+1029) is located very close to this object, being shifted only ≈ 3′ to the northwest. On the WISE 22 μm images it is rather bright.

This object resembles the central object of HH 588 flow, a compact HH object with very low excitation, located near the IRAS 21388+5622 source. It probably represents the very short jet from the exciting star (Ogura, Sugitani & Pickles 2002; Movsessian et al. 2012). So, one can assume that HH 1197 apparently propagates toward the southeast, away from the above mentioned infrared source.

3.1.6 HH 1196 flow

This chain of HH objects contains at least six distinct knots with diffuse emission between them; its total length is about 4′ (Fig. 8). All knots are aligned along an axis with position angle of 155°. Knots A, B, E and F have bow-shape morphology with apexes pointing in S-SE direction. This fact indicates that this group represents a single collimated outflow from a source, located in the northern direction.

As can be seen from Fig. 8, the relative intensities of the individual knots in Hα and [S ii] vary. Knots A, B, C and D are relatively brighter in Hα, while knot E has the ratio of Hα and [S ii] near 1, and knot F is seen mainly in [S ii].

Along the line connecting the HH 1196 knots, several objects, any of which can be suspected as a possible source of this outflow, can be found. The star associated with a small comet-like reflection nebula (No.7 in the list of Petrossian 1985, object s1 on Fig. 8) is located just between knots A and B; however, the morphology of bow-shaped knot A suggests the more distant north-western source location. Thus, as other and more probable sources of this outflow the YSOs IRAS 06297+1021 (E) (2MASS J06323082+1018396) and IRAS 06297+1021 (W) (2MASS J06322611+1019184) (s2 and s3 on Fig. 8), can be considered. Especially interesting is the IRAS 06297+1021 (W) source, which is rather bright in mid-IR range and has strong emission lines in IR spectrum. Some features in its spectrum also are in common with FU Ori-like objects (Connelley & Green 2010). In any case, these features indicate the existence of high-rate outflow activity in this YSO. Besides, IRAS 06297+1021 (W) is located close to the direct line, connecting all knots of HH 1196 outflow. If this object indeed is its source, the total length of HH 1196 outflow system is about 6′, which on the distance of 800 pc will be equivalent to about 1.4 pc, making it a parsec-sized outflow.

It is worth to mention that IRAS 06297+1021 (W), as well as IRAS 06297+1021 (E) are well visible in the optical range, but there are no data about their optical spectra. HH 1196 flow definitely deserves further study.

3.2 Stars associated with reflection nebulae

Being typical R-association, the investigated area contains significant amount of small reflection nebulae, connected with one or more stars. Several of these nebulae besides of being cataloged, never were studied in detail. Others are newly found objects, even not catalogued before. Several nebulae were described above in the appropriate subsections. We list the coordinates and short descriptions of all nebulous objects in our field in Table 2, excluding three brightest nebulae, identified in Fig. 1. Most interesting objects, especially
Table 2. The coordinates of supposed sources of HH flows and of stars associated with reflection nebulae in the observed field.

| Name          | RA(2000)   | Decl.(2000) | Other names                  | Notes                                                                 |
|---------------|------------|-------------|------------------------------|----------------------------------------------------------------------|
| IRAS 06277+1016 | 06 30 28.6   | +10 14 25.5 | 2MASS J06302857+1014236      | Far and mid IR source located in the apex of anon. cometary nebula    |
| HD 258686      | 06 30 47.1   | +10 03 46.4 | VdB 76                      | Star with nearby reflection nebula                                   |
| 2MASS J06305034+1037218 | 06 30 50.3   | +10 37 22.9 | Steine GN J0630.8+1037      | Star with tiny reflection nebula                                     |
| VY Mon/G2      | 06 31 06.9   | +10 26 05.0 | HBC 522                     | Small compact nebula, with no star inside                             |
| 2MASS J06311641+1022326 | 06 31 16.4   | +10 22 32.6 | Ber 92                      | Star with nearby reflection nebula                                   |
| LkHα 342       | 06 31 30.1   | +10 32 33.5 | HBC 204                     | Emission-line star enveloped by a small reflection nebula             |
| HD 258973      | 06 31 43.3   | +10 20 20.9 | VdB 79                      | Star with nearby reflection nebula                                   |
| 2MASS J06315782+1027360 | 06 31 57.8   | +10 27 36.0 | RNO 72, HHL 43a             | Brightest of three stars located in the apex of fan-like nebula       |
| 2MASS J06323082+1018396 | 06 32 30.8   | +10 18 39.6 | IRAS 06297+1021 (E)         | Faint star, can be associated with very faint reflection nebula       |
| 2MASS J06323159+1017352 | 06 32 31.6   | +10 17 35.2 | Petr 7                      | Star in the head of cometary nebula                                 |
| LkHα 216       | 06 32 52.4   | +10 18 43.1 | V490 Mon                    | Variable star, surrounded by tiny reflection nebula                  |

3.2.1 IRAS 06277+1016

This far-IR source is associated with reflection nebula and HH 1203 outflow. It is shifted 5″ to east from the optical nebula (see Fig.3). It coincides with bright WISE and Spitzer sources, while in 2MASS it is already non-stellar and elongated toward the optical reflection nebula. Such progressive shift in the source position depending on wavelength is typical for heavy embedded objects.
This tiny reflection nebula is located in 10′ to N-NW from IC 446 in a small dark cloud. It was listed among the results of a large search of new galactic open clusters (Kronberger et al. 2006), as Steine J0630.8+1037. The nearby (in 30′) source IRAS 06281+1039 can be related to this object. The nebula is connected with a red star (2MASS J06305034+1037218), which quite recently faded by one magnitude, according to data from Gaia transient survey (Gaia19drm). Without any doubts this object represents an active YSO; however, search in its vicinity did not reveal any HH objects.

This field actually includes two reflection nebulae. IC 446 itself consists of a blue nebula, bright in the optical range and illuminated by B2.5V TYC 737-255-1 (or IC 446 No. 1 star), and a rather bright and very red nebula, well seen even in FIR range. Its source, as was shown by Casey & Harper (1990), is VY Mon. Besides, we want to draw attention to a small, but compact and bright nebula, for the first time described by Maffei (1966), who also mentioned its probable variability. This nebula is designated as VY Mon/G2 in a fundamental survey of Cohen & Kuhi (1979). It is very close to VY Mon; however, according to the same survey, its spectral type is A0, while VY Mon itself is classified as O9. Nevertheless, more recent data give for the spectral type of VY Mon estimates between B8 and A5. Thus, it seems that this nebula indeed can be a dense knot of dust, illuminated by VY Mon. This object as HBC 522 was also included in the catalog of PMS stars (Herbig & Bell 1988). In any case, both our observation and 2MASS images as well do not show any stellar source inside VY Mon/G2.

This nebula is included in the early lists of red nebulous objects in dark clouds (Cohen 1980; Gyulbudagyan 1998). No further studies were performed. However, besides of our finding of a nearby HH 1197 knot, one should mention an interesting structure of this object as a whole.

The brightest part of this nebula has roughly fan-like shape, while filaments and other details can be traced up to 45-50′′ from the center (Fig.9, left). They can be seen also in Spitzer GLIMPSE360 color image (Fig.9, right). Though HH 1197 knot is clearly seen in PanSTARRS images (perhaps due to the continual component in its spectrum), there are virtually no traces of the above mentioned 2MASS source J06315870+1027474 in the optical range. Besides, there is a close group (<6.5′ in length) of three stars, embedded in RNO 72 itself; the brighter one (2MASS J06315782+1027360) is the probable illuminator of the optical nebula (Fig.9, left and center). All three stars are prominent sources in near IR and remain noticeably bright in longer wavelengths. Thus, one can conclude that in the center of RNO 72 exists a whole small cluster of PMS stars.

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The attention to the bright and large reflection nebulae NGC 2245 and NGC 2247 was drawn, when Herbig (1960) pointed that both nebulae are illuminated by young HAeBe stars LkHα 216 and HD 259431 respectively. In the same work it was also suggested that NGC 2245 can have biconical morphology, though it is not very well seen in the optical images. However, in Spitzer GLIMPSE360 survey the nearly perfect X-shaped nebular structure is obvious (Fig.10).

Analysing the mid-IR images of our field from Spitzer GLIMPSE360 and WISE surveys, we noted several knots arranged in chains and visible mainly in 4.5 μm bands both of Spitzer and WISE, but not detected in 3.6 μm. All of them are located in a very opaque area to the west from NGC 2247 nebula, around IRAS 06297+1021 (W) and (E)
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Figure 9. Objects in the field of RNO 72 nebula: color images from PanSTARRS survey (left panel), 2MASS survey (central panel) and Spitzer GLIMPSE360 survey (right panel). Numbers denote the following stellar sources: 1 - 2MASS J06315782+1027408, 2 - 2MASS J06315806+1027408, 3 - 2MASS J06315810+1027408, 4 - 2MASS J06315870+1027474 (IRAS 06292+1029). Star 2 was not resolved in 2MASS. Color coding for PanSTARRS: blue (g-band), green (r-band), red (i-band). Color coding for GLIMPSE360: blue (3.6 µm), green (4.5 µm), red (12 µm).

Figure 10. NGC 2245 nebula in Spitzer GLIMPSE360 survey. The bright star in the center is LkHα 215.

Figure 11. Three probable H2 flows, seen in Spitzer GLIMPSE360 survey. Two bright red objects near the center are IRAS 06297+1021 (E) and IRAS 06297+1021 (W) sources.

Table 3. The coordinates of probable H2 flows in the Mon R1 field.

| No. | RA(2000)  | Decl.(2000)  | Notes                          |
|-----|-----------|--------------|--------------------------------|
| Flow 1 | 06 32 40.9 | +10 19 37.3 | IR-source with narrow flow     |
| Flow 2 | 06 32 23.9 | +10 21 11   | At least two elongated knots   |
| Flow 3 | 06 32 39.8 | +10 18 19   | At least four knots            |

these flows can be understood only after further observations in 2.12 µm line, which are planned.

4 CONCLUSIONS

All presented above demonstrates that 1 m Schmidt telescope of Byurakan observatory, by means of which well-known surveys of active galaxies, as FBS and SBS, were conducted several decades ago, being equipped with modern light receivers, still can achieve important results.

The discovery of new directed outflows in Mon R1 association shows that the star formation in this area is significantly more active than appeared before and continues in the present time. This, in turn, indicates that Mon R1 contains a larger amount of low-mass active stars, among which can exist even such rare objects as FUor and EXor like stars.

Besides, the studied field covers only part of Mon R1; the area of IC 2169 with significant amount of emission-line stars also deserves study.

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REFERENCES

Casey S.C., Harper, D.A., 1990, ApJ, 362, 663
Cohen M., 1980, AJ, 85, 29
Cohen M., Kuhi L.V., 1979, ApJS, 41, 743
Connelley M.S., Greene T.P., 2010, AJ, 140, 1214
Dahm S.E, 2008, in Reipurth B., ed., Handbook of Star Forming
    Regions, Vol. I, Astron. Soc. Pac., p. 966
Dodonov S.N., Kotov S.S., Movsesyan T.A., Gevorkyan M. 2017,
Astrophysical Bulletin, 72, 473
Gutermuth R.A., Megeath S.T., Myers P.C., Allen L.E., Pipher
    J.L., Fazio G.G., 2009, ApJS, 184, 18
Gyulbudagyan A.L., 1998, Astrophysics, 41, 382
Herbig G.H., 1960, ApJS, 4, 337
Herbig G.H., Bell K.R., 1988, Lick Obs. Bull. No.1111, 1
Herbst W., Miller D.P., Warner J.W., Herzog A., 1982, AJ, 87, 98
Kronberger M. et al. 2006, A&A, 447, 921
Maffei P. 1966, Mem. Soc. Astron. Ital., 37, 459
Movsessian T.A., Magakian T.Yu., Sargsyan D. M., Ogura K.,
    2012, Astrophysics, 55, 471
Ogura K., Sugitani K., Pickles A. 2002, AJ, 123, 2597
Petrossian V.M., 1985, Afz, 22, 423
Racine R., 1968, AJ, 73, 233
Wang S., Looney L.W. 2007, ApJ, 659, 1360