Herbig-Haro flows around BBWo 192E (GM 1-23) nebula

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ABSTRACT

We studied a small comet-shape reflection nebula, located in the dark cloud SL 4 in the Vela Molecular Ridge cloud C, known as BBWo 192E (GM 1-23), and a young infrared cluster embedded into the nebula, for the evidences of recent star formation. We obtained the images of BBWo 192E in H\textalpha and [S ii] lines and in SDSS i' with Blanco telescope at the Cerro Tololo Interamerican Observatory to discover new Herbig-Haro (HH) flows. 2MASS and WISE surveys were used for the search of the additional member stars of the cluster. We also studied proper motions and parallaxes of the cluster members with the aid of GAIA DR2. Five new groups containing at least 9 HH objects tracing several distinct outflows were revealed. A previously unreported reflection nebula and a number of probable outflow sources were found in the infrared range. The proper motions allowed selecting eight probable member stars in the visual range. Their parallaxes correspond to a mean distance $800 \pm 100$ pc for this cluster. The bolometric luminosities of the brightest cluster members are $10^{10}$ $L_{\odot}$ (IRAS 08513–4201, the strong source in the center of the cluster) and 2 to 6 $L_{\odot}$ for the five other stars. The existence of the optical HH flows around the infrared cluster of YSOs suggests that star formation in this cloud is on-going around the more massive HAeBe star. By its morphology and other features this star-forming region is similar to the zone of star formation near CPM 19.

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

1 INTRODUCTION

A small comet-shape reflection nebula, located in the elongated dark cloud SL 4 (Sandqvist & Lindroos 1976) in the Vela Molecular Ridge cloud C (Murphy & May 1991), is known as GM 1-23 (Gyulbudaghian & Magakian 1977) and BBWo 192E (Brand, Blitz & Wouterloot 1986). Such nebulous objects are often indicators of ongoing star formation and this case is no exception. The survey of Pettersson & Reipurth (1994) revealed tens of H\textalpha emission-line stars in the vicinity of SL 4, but did not find any Herbig-Haro (HH) objects. The BBWo 192E nebula was studied for the first time in this work; the authors concluded that it was a reflection nebula and that the relatively bright star on its northern edge is a projected foreground object. They suggested that the illuminating star is embedded in the cloud and should be HAeBe type young star.

This BBWo 192E nebula is associated with a bright and very red source, IRAS 08513–4201, recognized as a Class I object with a near-IR counterpart (Liseau et al. 1992). Further multi-frequency studies (Burkert et al. 2000; Massi, Lorenzetti & Giannini 2003; Dutra et al. 2003) in the near and mid-infrared revealed a young infrared cluster embedded in the nebula. IRAS 08513–4201 was found to be its most luminous member, illuminating not only the optical nebula but also a bipolar IR reflection nebula. The distance of this group was estimated by Burkert et al. (2000) $\sim$1.2 kpc. These findings led us to search for HH objects and collimated outflows in the BBWo 192E field with narrow-band filters.

2 OBSERVATIONS AND DATA REDUCTION

The images presented here were obtained on the nights of 13 May 2004 using the NOAO Mosaic II Camera CCD camera at the f/3.1 prime focus of the 4 meter Blanco telescope at the Cerro Tololo Interamerican Observatory (CTIO) near La Serena, Chile. Mosaic II camera is a $8192 \times 8192$ pixel array (consisting of eight $2048 \times 4096$ pixel CCD chips) with

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Table 1. List of the new HH objects

| Knot  | α(J2000) h m s | δ(J2000) ° ′ ′′ |
|-------|---------------|------------------|
| HH 1204 | 08 53 08.1  | -42 12 10        |
| HH 1205C | 08 53 02.8  | -42 13 14        |
| HH 1205B | 08 58 07.0  | -42 12 49        |
| HH 1205A | 08 53 09.5  | -42 12 34        |
| HH 1206  | 08 53 10.9   | -42 14 13        |
| HH 1207A | 08 53 14.0   | -42 14 10        |
| HH 1207B | 08 53 12.7   | -42 14 07        |
| HH 1208A | 08 53 13.1   | -42 14 34        |
| HH 1208B | 08 53 12.9   | -42 14 41        |

a pixel scale of 0.26″ pixel⁻¹ and a field of view 35.4′ on a side.

Narrow-band filters centered on 6569 Å and 6730 Å with a FWHM bandwidth of 80 Å were used to obtain Hα and [S ii] images. A Sloan Digital Sky Survey (SDSS) i’ filter centered on 7732 Å with a FWHM of 1548 Å was used for continuum imaging. A set of five dithered 600 second exposures were obtained in Hα and [S ii] using the standard MOSDITHER pattern to eliminate cosmic rays and the gaps between the individual chips in Mosaic. A dithered set of five 180 second exposures were obtained in the broad-band SDSS i-band filter to discriminate between Hα, [S ii], and continuum emission.

Images were reduced in the standard manner using IRAF. Following bias subtraction, cosmic ray removal, and flat fielding using dome flats, images were combined using the MSCRED package in IRAF. Due to insufficient observational time over the whole images there are remaining parts with low S/N.

3 RESULTS

3.1 Visual wavelength imaging

The images reveal several small shock-excited emission nebulae in two or three groups seen in the H-alpha and [S ii] narrow-band filters but not in the broad i’-band filter. Given their morphology, they are likely to be HH objects which are too faint to have been seen in the previous searches. Their coordinates are given in Table 1 and images are shown on Fig. 1 and Fig. 2, Fig. 3, where they can be seen better, shows the subtraction of a scaled version of the i’-band image from the [S ii] image, with the intensity adjusted so that stars have similar counts in the i’ and [S ii] images. The brightest part of BBWo 192E nebula also remains visible in this figure, which may indicate the presence of reflected emission from the central source. We checked the DECaPS survey (Schlafly et al. 2018) in which these HH objects are also detected. However, they cannot be distinguished by color from the other red stars and nebulous wisps.

As seen in Figs. 1 – 3, all HH knots are brighter in [S ii] emission. One group of HH objects is located near the northern side of reflection nebula. Two elongated streaks superimposed on the BBWo 192E nebula, labeled as knots A and HH objects are marked by arrows.

Figure 1. BBWo 192E nebula and new HH objects around it in [S ii] filter. Rectangular artifacts are produced during the image processing.

Figure 2. Same field in Hα filter.

Figure 3. Same field in [S ii] filter after continuum subtraction. HH objects are marked by arrows.
B in Fig. 3, along with knot C located north of the reflection nebula core, form the chain we call HH 1205. The three components, HH 1205 A, B and C, form a nearly straight line and therefore probably trace shocks in one outflow with a full extent of about 85′′, corresponding to a projected length about a half of parsec at the assumed distance to this complex. To be sure that the streak HH 1205 B is a real emission structure and not a remnant of continuum subtraction, we want to note that it is invisible in Hα image and, on the other hand, the brighter nebulosity structure, located to the south from it, is completely subtracted in Fig. 3.

HH 1204 is an arcuate feature located about 30″ north of the HH 1205 chain, practically visible only in [S II].

A second group of HH objects, HH 1206, HH 1207, and HH 1208, located about 90 to 120″ southeast of BBWo 192E. HH 1206, resembles a bow-shock containing several small knots. HH 1207 consists of two streaks elongate east-to-west and may trace parts of a collimated flow. HH 1208 comprises two nearly-stellar knots. They are projected on several faint, nebulous wisps which may be reflection nebulae, given their visibility in the i′ image.

Thus, the BBWo 192E field contains at least 9 HH objects tracing several distinct outflows. However, none are associated with visual wavelength stars that are likely driving sources. The stars that drive these outflows are more likely to be highly obscured. The observed HH objects may trace material ejected from the cloud into the relatively extinction-free foreground.

3.2 Infrared data

We searched the literature for near-IR studies and inspected several public-domain data sets such as 2MASS and WISE to search for the probable driving sources these HH objects. Dutra et al. (2003) found a small infrared cluster (#22 in their list) associated with BBWo 192E, the existence of which was also suspected in the study of Burkert et al. (2000). This cluster includes also a small nebula, which is the IR analog of BBWo 192E, and is seen in the 2MASS survey (Fig. 4). Star #28 from the work of Burkert et al. (2000), visible only at IR wavelengths, coincides with the straight line connecting HH 1205 A, B and C. As is discussed in the same paper, star #28 is likely to be a pre-main-sequence (PMS) star inside the cloud. It has very red colors according to Massi, Lorenzetti & Giannini (2003, star IRS 26-35) and is a likely candidate source powering the HH 1205 outflow. There are no infrared sources near HH 1204.

The near-IR (J, H, K-band) 2MASS images reveal another small, near-IR reflection nebula ∼2′ to southeast of BBWo 192E in the vicinity of the southeastern group of HH objects (see Fig. 4); 2MASS 0.00 coordinates, RA = 8° 53′ 15″, Dec = −42° 14′ 31″). This nebula is not seen in the visual wavelength images and was not previously mentioned in any catalogs or surveys. The 2MASS Point Source Catalog lists seven sources inside the nebula, at least some of which may be embedded young stars. Thus, the existence of a compact infrared cluster of PMS stars inside this nebula seems probable. HH 1206 and HH 1207 are located northwest of this wedge-shaped IR reflection nebula; HH 1206 is close to its axis of symmetry. However, it is unclear which, if any of the IR sources, visible in this region, powers HH 1206, 1207, and 1208.

Figure 4. Color representation of the investigated field from 2MASS survey (J - blue, H - green, K - red). Two infrared nebulae are prominent. The positions of HH objects are marked by white crosses. Star #28 a.k.a. IRS 26-35 (Burkert et al. 2000; Massi, Lorenzetti & Giannini 2003) is pointed by arrow.

The near-IR (J, H, K-band) 2MASS images reveal another small, near-IR reflection nebula ~2′ to southeast of BBWo 192E in the vicinity of the southeastern group of HH objects (see Fig. 4); J2000.0 coordinates, RA = 8° 53′ 15″, Dec = −42° 14′ 31″. This nebula is not seen in the visual wavelength images and was not previously mentioned in any catalogs or surveys. The 2MASS Point Source Catalog lists seven sources inside the nebula, at least some of which may be embedded young stars. Thus, the existence of a compact infrared cluster of PMS stars inside this nebula seems probable. HH 1206 and HH 1207 are located northwest of this wedge-shaped IR reflection nebula; HH 1206 is close to its axis of symmetry. However, it is unclear which, if any of the IR sources, visible in this region, powers HH 1206, 1207, and 1208.

Figure 5. Color image of a wide field around BBWo 192E from WISE survey (blue - 3.3 μm, green - 4.7 μm, red - 22 μm). The area, presented in Figs 1–4, is shown by white square.

The clustering of embedded sources around BBWo 192E is apparent in the longer mid-IR WISE survey (λ = 3.3, 4.7, 12, and 22 μm; Wright et al. 2010) (Fig. 5). Wider field-of-view images reveal several additional infrared sources in the region. IRAS 08513–4201, located near the apex of the BBWo 192E nebula, dominates the field. Many additional sources not seen in the 2MASS images are also visible. The most prominent objects are marked in Fig. 6 and described below. Their designations are those of the allWISE source catalog along with the numbers from the list of J, H, and K photometry by Massi, Lorenzetti & Giannini (2003).

J085309.91-421232.6 (IRS 26-35). This source was discussed above. The WISE data confirm its large mid-IR...
brightness which peaks at 22 μm (no longer-wavelength photometric data can be found), making it likely to be a young stellar objects (YSO). It may be the source of the HH 1205 outflow. J085313.68-421301.6 (IRS 26-19). This source, located 48″ east from IRAS 08513–4201, is absent at all 2MASS wavelengths but visible in the WISE 3.3 μm image. It becomes prominent at longer wavelengths, second only to IRAS 08513–4201. It illuminates the cone-shaped IR reflection nebula, oriented northward. It is invisible in the 2MASS K-band and in the K-band image in Burkert et al. (2000). However, it appears near the limit (K = 16.85) in the image presented by Massi, Lorenzetti & Giannini (2003) which makes it one of the reddest objects in the field.

J085312.79-421355.2 (IRS 26-52). This object located between two IR reflection nebulae described above is absent in the 2MASS catalog, but according to Massi, Lorenzetti & Giannini (2003) is brighter (K = 15.39) than the previous object. On WISE images it appears embedded in the faint nebula. However, it is not as red as J085313.68–421301.6.

J085314.89-421411.4 and J085314.29-421420.2. This is a pair of the sources on the north-western side of the newly described IR reflection nebula. They are located outside of the area, studied by Massi, Lorenzetti & Giannini (2003). The eastern source is brighter in near IR and can be found in the 2MASS all-sky PSC; the western source becomes brighter at 12 μm in the WISE image. These sources may be the main illuminators of the reflection nebula. They are candidate drivers of the outflows containing HH 1207 and HH 1208.

3.3 Proper motions and distance

Most stars in the IR cluster inside BBWo 192E are invisible in the visual wavelength range. Nevertheless, new astrometric data from the GAIA DR2 catalog allow a search for additional members of this cluster which are not too embedded.

We studied the field around IRAS 08513–4201 within a 3′ radius. The GAIA DR2 catalog contains 61 stars. From these we selected stars with parallaxes in the 0.7–1.8 mas range, taking into account the systematic correction +0.045 mas (see, e.g. Schönhich, McMillan & Eyher 2019). The exact value of this correction is not significant at the distances less than 1 kpc.

Fig. 7 shows the distribution of their proper motions (PM) in right ascension and declination. There are 8 stars with similar proper-motion values. These stars have similar parallaxes (see Fig. 8) with a mean value of 1.32 ± 0.18 mas corresponding to a mean distance 800 ± 100 pc. Their mean PM is −4.89 ± 0.19 mas/y (RA) and +3.17 ± 0.28 mas/y (Dec). One more argument for the possible relationship between this group of stars and the IR cluster is their very red colors (BP–RP values are in 2.5–3.7 range).

There are 6 additional faint stars with G magnitude in the 18.5–20.2 range whose PMs are similar to the 8 brighter stars, but their parallax and proper-motion errors are large. Thus, these stars may also be members of the cluster. However, they are located at greater projected distance from the center of the cluster than the eight selected stars.

We show the positions of eight probable member stars in Fig. 9. For completeness, in Table 2 we list their positions and distances according to the catalogue of Baider-Jones et al. (2018). These distances are estimated by the Bayes method, taking into account selection effects. The mean distance, computed by these data, is 940 pc. The difference in values can be explained by various corrections for the systematic error in parallaxes.

Six of these stars have IR photometry in Burkert et al. (2000), three in Massi, Lorenzetti & Giannini (2003). One of these stars is an emission-line star, ESO-Ho 259 (Pettersson & Reipurth 1994).

Finally, assuming that some of the nebulous stars in the investigated field belong to SL 4 dark cloud, we selected...
Table 2. List of the probable members of BBWo 192E cluster

| DR2Name | RA (ICRS), degr | Dec (ICRS), degr | Distance, pc | Most probable | Min | Max |
|---------|----------------|-----------------|--------------|---------------|-----|-----|
| Gaia DR2 5524333136802415232 | 133.24088919944 | −42.24554393145 | 733 | 468 | 1573 |
| Gaia DR2 5524356744444023168 | 133.27889063691 | −42.29056943224 | 931 | 860 | 1005 |
| Gaia DR2 5524356608803767680 | 133.2604332165 | −42.22976576506 | 1143 | 1030 | 1283 |
| Gaia DR2 5524356707582560176 | 133.30762774432 | −42.20570767714 | 924 | 804 | 1084 |
| Gaia DR2 5524356673223197440 | 133.28786696999 | −42.22603423908 | 1493 | 674 | 3149 |
| Gaia DR2 5524356845021802240 | 133.25994547813 | −42.21249223335 | 791 | 667 | 970 |
| Gaia DR2 5524356845021803392 | 133.25961283028 | −42.20670598232 | 804 | 624 | 1124 |
| Gaia DR2 5524356879381541632 | 133.24276963092 | −42.20732210284 | 709 | 605 | 855 |

Table 3. Emission and nebulous stars probably related to SL 4 dark cloud

| Gaia DR2 name | Other names | Nebula | Distance, pc | Most probable | Min | Max |
|---------------|-------------|--------|--------------|---------------|-----|-----|
| 552452218442923520 | ESO-Ho 2348 | BBWo 192C | 865 | 839 | 893 |
| 5524545823586550400 | BBWo 192D, GN 08.51.1.01 | 968 | 768 | 1301 |
| 5524519989361683840 | ESO-Ho 249 | BBWo 192B, GN 08.50.5 | 1028 | 1004 | 1053 |
| 5524357742675055232 | ESO-Ho 260 | 958 | 876 | 1055 |
| 5524520019419933824 | ESO-Ho 248 | 962 | 880 | 1060 |

Figure 8. The correlation between visible magnitudes and parallaxes for all stars in BBWo 192E field, measured in GAIA DR2. The stars with parallaxes in 0.7–1.8 mas range are shown by blue, stars with similar PM – by green. All other stars in the field are marked with red color.

Figure 9. Eight stars with close PM and distances, which are the probable members of BBWo 192E cluster, are marked by white squares on the color image of the field, taken from DECaPS survey.

10 objects from the list of Pettersson & Reipurth (1994) and BBWo catalog. With the aid of Plx-Gmag and PM diagrams we excluded ESO-Ho 244 as a foreground object and ESO-Ho 255, 256 and 257 as background objects. ESO-Ho 258 has large measurement errors. The remaining 5 stars are listed in Table 3 with their distances from the catalogue of Baier-Jones et al. (2018). Their mean distance is 960 ± 50 pc, which confirms their belonging to SL 4 cloud. However, these nebulae and emission-line stars are slightly more distant than the probable member stars of the BBWo 192E cluster, located in the most opaque part of the cloud.

GAIA DR2 shows that our distance estimate of 800±100 pc to the SL 4 cloud is lower than the previously estimated distance (Burkert et al. 2000). Our determined distance is similar to the 866 to 965 parsec distance of the Vela Complex (Zucker et al. 2020). For the further estimations of bolometric luminosities we use 800 pc value as based solely on the stellar parallaxes.
4 DISCUSSION AND CONCLUSION

The most luminous infrared source in the BBW 192E cluster, IRAS 08513–4201 (also known as IRS 26-15), was analyzed in Pettersson & Reipurth (1994) and Burkert et al. (2000). It can be unambiguously identified with 2MASS 08530946–4213076 and WISE J085309.32–421397.3. The 2MASS point source catalog lists two more nearby sources (08530938–4213051 and 08530898–4213093), but the close inspection shows that they probably represent the brightest parts of the IR reflection nebula. We added photometry from the MSX6C catalog (Egan et al. 2003), the AKARI/IRC mid-infrared all-sky survey, and sub-mm observations using the BLAST telescope (Netterfield et al. 2009) to build the spectral energy distributions (SED) for this object. The SED of IRAS 08513–4201 is shown in Fig. 10. The SED is broad, suggesting a wide range of dust temperatures. We estimate bolometric luminosity of IRAS 08513–4201 to be \( \sim 10^{10} L_\odot \), slightly lower than previous estimates because of the smaller adopted distance. This object is likely to be an intermediate-mass HAEBe star.

Fig. 11 shows the SEDs of other IR sources, described in Sec. 3.2. These SED use photometry from 2MASS and allWISE since they were not detected in longer wavelength surveys. All of these objects emit at wavelengths longer than 2 \( \mu \)m which demonstrates high foreground extinction. We estimated lower-bounds on their luminosities by integrating the SEDs over the observed range. Their luminosities range from \( L > 0.5 \) to 2.9 \( L_\odot \). Since no far-IR data exist, we computed the bolometric corrections using the approach suggested by Cohen (1973). The corrected bolometric luminosities of these 5 sources range from 2 to 6 \( L_\odot \) with J085309.91–421232.6 (IRS 26-35) being the most luminous. Thus, these are typical T Tauri class stars. Thus, the SL 4 cloud contains a small group of forming and young low mass stars surrounding a more massive HAEBe star.

An interesting feature of the SL 4 cloud is the absence of any HH flows connected to IRAS 08513–4201, the most luminous source. On the other hand, the existence of the optical HH flows around both the reflection nebulae and the cluster of YSOs suggests that star formation in this cloud is on-going. Assuming a typical flow velocity of 100 km s\(^{-1}\) and a characteristic separation of the HH objects from likely sources, their kinematic ages cannot be more than several thousand years. The presence of some YSOs and ionized flows in the visual wavelength images indicates that some members of this group of young stars are not heavily embedded in the dark cloud, and the significant part of line-of-sight extinction can be produced in the dusty circumstellar disks and envelopes.

The SL 4 star-forming region is similar to the zone of star formation near CPM 19 (Khanzadyan et al. 2011, and references therein). SL 4 may be an interesting target for the study shock-excited \( \text{H}_2 \) emission. Multi-epoch monitoring would be useful for the identification of erratic variables and occasional multi-magnitude accretion-powered flares. Unfortunately, this field was not observed by either the Spitzer or Herschel surveys. If the BBWo 192E nebula is illuminated by IRAS 08513–4201, then its visual wavelength or near-IR spectrum could be obtained by observing the reflection nebula it produces. Such a study could provide further insights into the mass and evolutionary state of this embedded object. Finally, given its southern location, the BBWo 192E star forming region is ideally placed for deep millimeter and sub-millimeter-wave studies with ALMA.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
New HH objects around BBW 192E

Figure 11. SEDs of other IR sources in the vicinity of IRAS 08513−4201.

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