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A new star-forming region in CMa†

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A new southern star-formation region is described. It is located in the L 1664 dark cloud, near to CMa OB1. Several compact stellar clusters and small groups, embedded in dark cloudlets, are located in this area. Using the images obtained with 4-m CTIO telescope, more than 20 Herbig–Haro knots, combined in several outflows, were found. Many of young stars are connected with small reflection nebulae. The distance of this region is assumed to be about 1.5 kpc but can be even higher.

Keywords: Open clusters and associations, ISM: Herbig–Haro objects, jets and outflows

1 Introduction

In the process of a search for cometary nebulae and HH objects candidates on the Palomar Observatory Sky Survey (POSS) images (Gyulbudaghian and Magakian, 1977a,b,c) a group of the several faint nebulous objects were found around RA = 7h 24m and Dec = −24d 30m. These objects are associated with the L 1664 dark cloud far from the well-known star forming regions (SFRs) such as CMa OB1 and CMa R1. At the time of their discovery, the large negative declination prevented acquisition of better images. Surveys of this region identified several other reflection nebulae listed in Brand, Blitz and Wouterloot (1986). No additional data became available in the subsequent decades and this region remains poorly studied, especially at visual wavelengths. In this paper, we present deep narrow-band Hα and [SII] images of the L 1664 cloud and report the presence of several new Herbig–Haro (HH) flows.

2 Observations

The images were obtained on the night of 13 May 2004 using the NOAO Mosaic II Camera CCD camera with 8192×8192 pixel full array at the f/3.1 prime focus of the 4

† This is the short version; the full paper will be published elsewhere

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meter Blanco telescope at the Cerro Tololo Interamerican Observatory (CTIO) near La Serena, Chile. Narrow-band filters centered on 6569 Å and 6730 Å both with a FWHM of 80 Å were used to obtain Hα and [SII] images. An SDSS i' filter centered on 7732 Å with a FWHM of 1548 Å was used for continuum imaging.

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.

3 Results

3.1 HH objects and HH flows

The HH knots and flows were identified by comparison of Hα, $\lambda\lambda$ 6716/6731 Å [SII] emission, and broad-band SDSS i' band images. Several new groups of the HH objects were found. The area studied contains many dark cloudlets. However, outflow activity as indicated by the presence of HH objects is confined to a small portion of the L 1664 cloud. All detected HH are concentrated along a northeast-southwest line connecting three groups of small reflection nebulae around BBWo 22C, GM 1-8 and GM 3-7 nebulae with one exception.

The new HH objects are listed in Table 1 in the order of their right ascension. Below we describe two most interesting groups.

Table 1 The coordinates of HH objects and HH flows.

Name	RA(2000)	Decl.(2000)	Notes
HH 1108	7 23 55.1	−24 39 57	Streak with condensations
HH 1109	7 24 11.9	−24 38 33	To the SW from BBWo 22C
HH 1110	7 24 18.4	−24 36 42	To the NE from BBWo 22C
HH 1112	7 24 41.5	−24 34 15	To the NE from GM 2-20
HH 1111A	7 24 43.6	−24 19 32	A separate flow from embedded source
HH 1111B	7 24 43.2	−24 19 46	
HH 1111C	7 24 43.0	−24 19 49	
HH 1111D	7 24 42.6	−24 19 45	
HH 1113	7 24 45.2	−24 33 40	To the NE from GM 2-20
HH 1114	7 24 45.4	−24 31 13	Star-like HH knot with reflection nebula
HH 1120A	7 24 46.2	−24 33 05	Faint spot
HH 1120B	7 24 48.0	−24 33 00	Two faint knots
HH 1120C	7 24 48.3	−24 32 59	
HH 1116	7 24 50.2	−24 29 23	Two faint knots
HH 1115	7 24 51.5	−24 29 23	HH jet from the star in GM 2-21 nebula.
HH 1117	7 24 55.3	−24 28 39	Small knot
HH 1118A	7 24 56.6	−24 28 10	Several bright knots in common nebula
HH 1118B	7 24 56.8	−24 28 11	
HH 1118C	7 24 57.0	−24 28 11	
HH 1119A	7 24 58.0	−24 31 12	A dumbbell-like pair of HH knots
HH 1119B	7 24 58.7	−24 31 10	

3.1.1 GM 3-7 group

Figure 1 shows a small group of nebulae located in the northeastern part of the studied area. The GM 3-7 (BBWo 22F) is a compact nebula surrounding several stars. No trace of HH emission was detected inside this object. At visual wavelengths, it includes two stars of nearly equal brightness and one more faint. In 2MASS K_s image yet another star becomes visible.

GM 1-22 (BBWo 22H) is a bright star on the edge of a dark cloud that illuminates compact fan-shaped reflection nebula with high surface brightness. In our early search on POSS images, two small red nebulae were found near southeast and northwest sides of GM 1-22 (Gyulbudaghian and Magakian, 1977b), thought to be candidate HH objects and listed as GM 2-21 and GM 2-22. GM 2-22 (incorrectly labeled in SIMBAD as the same object as GM 1-22) is actually a galaxy which is listed as a zone of avoidance object ZOAG G238.44-04.08. The object GM 2-21 is a classical cone-type cometary nebula with a red star in the head of the cone. It can be associated with IRAS 07227-2423 source, which is only in 11″ distance from this star.

Several objects with HH-type emission, found in this field, are shown in Fig. 1. HH 1114 is a nearly star-like emission knot especially bright in [SII] image but also

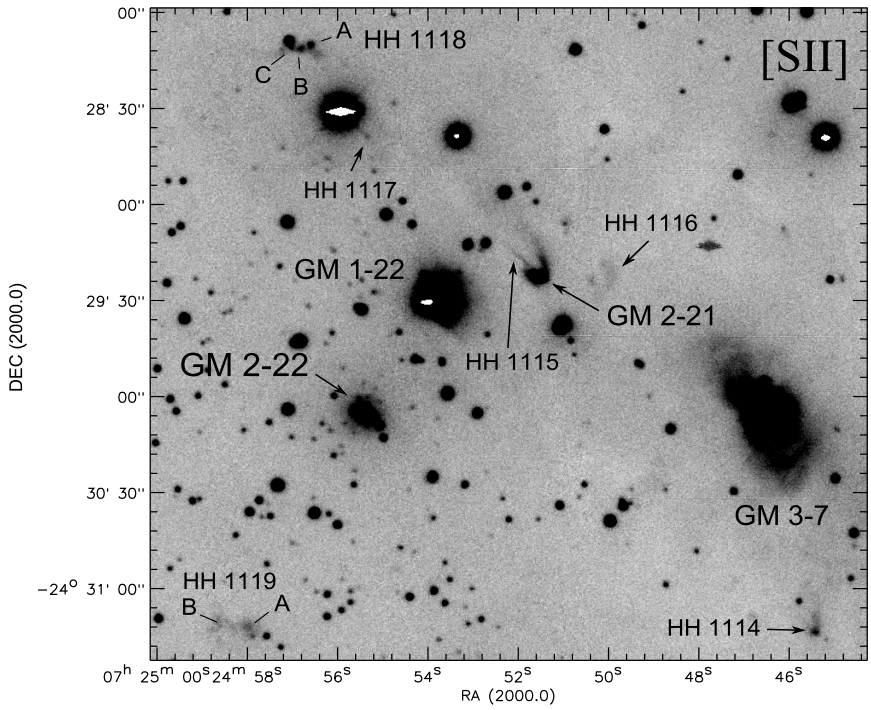


Figure 1 An [SII] image of the area surrounding GM 1-22 and GM 3-7. The HH objects, HH jets and reflection nebulae are labelled. Also note that GM 2-22 is a galaxy ZOAG G238.44-04.08.

seen well in Hα. It is accompanied by nebulous wisps, which may have a pure reflection nature, being also bright in the i' image where the knot is absent. Thus, as whole, HH 1114 resembles a cometary nebula, oriented roughly in SW-NE direction with the emission-line core. The nebulosity is faintly detected in the J and H 2MASS images but in K_s a star-like object coincides with the emission-line knot. HH 1114 may contain a star, heavily embedded in the circumstellar dust torus, seen edge-on but enveloped in HH emission like T Tau or HH 30. The existence of reflection nebula shows that some light is escaping through the torus inner cavity.

HH 1115 is similar to HH 1114. The HH object is well-defined in [SII] and exhibits a collimated jet which extends from the red star in the apex of GM 2-21 along the nebula axis in southwest-northeast orientation.

In addition to these cases, there are another four HH objects in this field. HH 1116 is a faint spot to the west from GM 2-21 visible mainly in [SII]. HH 1117 is a compact knot which contrary to other HH objects in this area is brighter in Hα. HH 1118 is similar in appearance in [SII] and in Hα. It consists of three compact bright knots A, B and C (knot C is very close to a star), which are connected with a nebulous filament. HH 1117 and HH 1118 are located close to the axis of the HH 1115 jet and may trace the same outflow. HH 1119 consists of a pair of nebulous patches with the appearance of a dumbbell and is brighter in [SII] than Hα. It is projected on the field with low extinction and is somewhat separated from the other HH objects around GM 3-7.

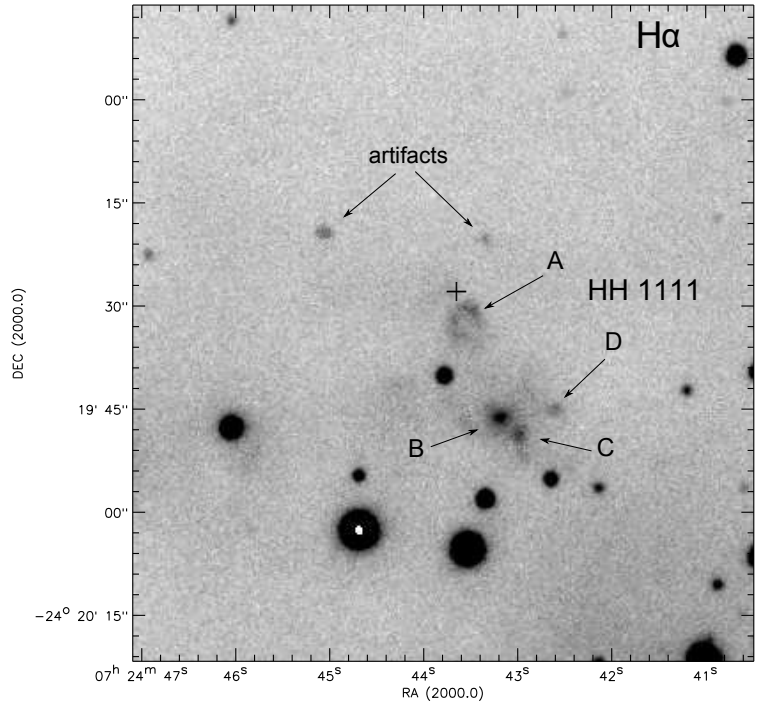


Figure 2 The HH flow near embedded IR source in Hα emission. The individual knots are marked by letters. The position of IR star is shown by cross.

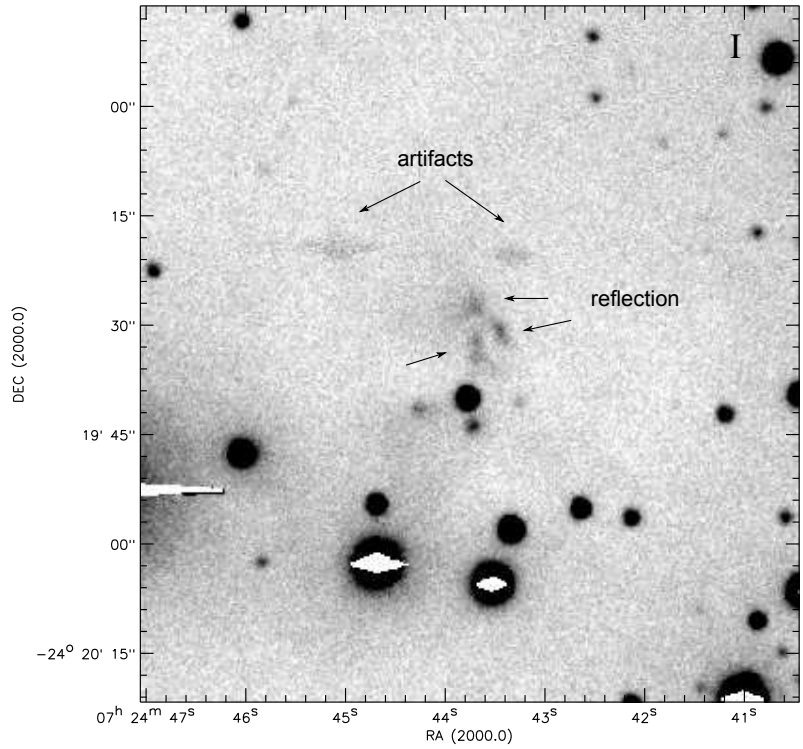


Figure 3 The same area in the i' filter. Instead of HH knots, one can see reflection patches, tracing the conical cavity.

3.1.2 A group near embedded IR source

HH 1111 is located near the edge of dark cloud and is detached from the main area of HH activity in the studied field. Its structure is shown in Fig. 2. The central star is totally invisible in optical range but is seen in the 2MASS H-band and especially K_s images as a point source. In [SII] and especially in Hα one can detect several distinct emission knots, surrounded by extended nebulosity, all of which are located southwest of the IR star. The knots are designated as HH 1111 A, B, C, D in Fig. 2. The knots are totally absent in the i' image (Fig. 3) but few very faint reflection patches, which probably trace the walls of conical cavity, created by the flow, can be seen near the position of the knot A. It appears that emission knots are distributed in a wide sector with an opening angle about 45°. Thus, HH 1111 flow seems to be not well-collimated and propagating in a wide cone.

3.2 Reflection and cometary nebulae

The investigated area contains many small reflection nebulae which are associated with one to several stars. Thus, the L1664 cloud may be an example of an association or reflection nebulae (R-association in the older literature). Most of these nebulae are associated with bright stars and were listed in BBWo and GM catalogues but were

Table 2 The coordinates of the reflection and cometary nebulae in the field.

Name	RA(2000)	Decl.(2000)	Other names	Notes
RN 5a	7 23 40.1	−24 43 42		A patch with two stars
RN 5b	7 23 41.7	−24 43 40		
BBWo 22A	7 23 51.9	−24 46 00		Three stars in nebula
BBWo 22B	7 24 01.0	−24 24 04		Bright star with a faint nebula
RN 1	7 24 05.9	−24 38 53		Nebulous star near BBWo 22C
BBWo 22C	7 24 14.1	−24 38 16	GN 07.22.1, RK 71	Includes IR cluster DBS 11
RN 2	7 24 22.5	−24 35 49		Nebulous star near BBWo 22C
BBWo 22D	7 24 31.1	−24 41 37		Bright star with a faint nebula
GM 1-8	7 24 37.0	−24 34 47	GLMP 181, PDS 250	IRAS 07225-2428 associated
RN 6	7 24 38.8	−24 28 11		Typical cometary nebula
GM 2-20	7 24 40.5	−24 34 23	BBWo 22E[a]	
RN 3	7 24 40.8	−24 35 33		Filamentary reflection nebula
RN 7	7 24 43.9	−24 31 57		A nebulous star
RN 4	7 24 44.4	−24 35 08		A nebulous star
RN 8	7 24 46.2	−24 31 55		A star with nebulous fan
GM 3-7	7 24 46.7	−24 30 00	BBWo 22F[b]	Contains several stars
BBWo 22G	7 24 47.5	−24 41 20		Bright star with a faint nebula
GM 2-21	7 24 51.4	−24 29 23		Typical cometary nebula
GM 1-22	7 24 54.0	−24 29 30	BBWo 22H	

[a]in SIMBAD is identified incorrectly
[b]in SIMBAD is incorrectly identified with GM 2-21

never studied in detail. Several other nebulae represent newly discovered objects whose illuminating stars are faint. Some are directly connected with HH objects or located near the outflows. For completeness and to avoid the problems of misidentification, we list all new and previously catalogued reflection nebulae with the correct coordinates in Table 2.

4 Conclusion

The limited amount of the observational data available does not enable a thorough analysis of this star-forming region. The distance remains unknown. However, the compact sizes of the reflection nebulae, the appearance of HH objects, and high density of foreground stars despite being in the anti-center direction suggest that this cloud is much farther than the Taurus, Ophiuchus, or Perseus complexes, and possibly more distant than Orion or the North America / Pelican Nebula complex in Cygnus.

Within a half degree of the L1664 dark cloud one can find several other dark clouds such as L 1667, which contains the GM 1-46 nebula (Gyulbudaghian and Magakian, 1977a) and the Bok globule L 1660, which includes HH 72, several emission-line young stars and reflection nebulae (Reipurth and Graham, 1988). The [SII] and especially

the Hα images show extended diffuse emission on the Western side of the image. This emission may belong to the rather large and diffuse HII region Sh-2 310. It is difficult to determine where the dark clouds are located – in the foreground or behind the emission.

The distances to these clouds and the HII region Sh-2 310 are controversial. In Reipurth and Graham (1988) these dark clouds were assumed to be related to the Vela OB1 association at a distance of 1.5 kpc. However, there are also other estimates. In Vieira et al. (2003) the central star (PDS 250) in GM 1-8 was studied. It was not listed as the member of Vela OB1 or any other known SFR and its distance was given as 2460 pc (probably kinematic, from radio observations) or even 4100 pc (photometric).

L 1664 dark cloud is associated with at least two photometrically studied IR star clusters. One, DBS 11, is located inside the BBWo 22C reflection nebula and is also connected to two HH objects. This cluster is clearly associated with L 1664. Its (J−H),(H−K_s) diagram (Soares et al., 2008) demonstrates that the cluster contains low-mass young stars. Unfortunately, the distance is not estimated. The range of A_V from 9 to 17 magnitude, given by Ivanov et al. (2002) seems definitely overestimated given their ready visibility in the images presented here. Soares et al. (2005) consider nearly all the stars surrounding GM 2-20 and GM 1-8 nebulae as an another small cluster. Using the (J,(J−H))$_0$ diagram they estimate the distance modulus J−M_J as 10.5 and give a distance of 1.3 kpc. Though this value is lower than estimates of Vieira et al. (2003), it seems in good agreement with the distance of Vela OB1. Finally, the distance to the well-studied cluster NGC 2362, which is believed to ionize the Sh-2 310 HII region, also is established as 1.5 kpc (Dahm, 2008).

Thus, we assume that L 1664 and all objects inside it are located at D = 1.5 kpc, though this should be verified in the future. The longest flow in the field – from GM 2-21 to HH 1118 – has the projected length of 0.75 pc at this distance. The full projected length of the long axis of the star forming region itself will be about 8 pc. This value seems slightly low, if we consider that it contains several open clusters and stellar groups. But, taking into account the work of Kumar et al. (2006), where a large amount of just the similar embedded young clusters is studied, one can see that more than half of them have effective radii of 1.5 pc and smaller. Thus, if we assume 1.5 kpc as the distance of L 1664 star forming region, the observed sizes of embedded clusters will be in a good agreement with these data.

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