Near-Infrared Survey of Bright Rimmed Clouds

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(Received 2011 December 9; accepted 2012 March 13)

Abstract

We conducted wide-field near-infrared imaging observations of 32 bright rimmed clouds (BRCs). Given a detection limit of 17.7 mag at the K-band, we identified 2099 objects as young stellar object (YSO) candidates that displayed near-infrared excesses. Their masses, estimated from luminosities, range from 0.006 $M_\odot$ to 2.7 $M_\odot$. The candidates are not uniformly distributed. For 21 BRCs, more than half of the associated YSO candidates are located inside the cloud. We found clear evidence of triggered star formation. The number of YSO candidates is not correlated with the core mass of the molecular clouds. Instead, the YSO number increases with increasing UV photon flux from the exciting star illuminating the cloud surface. UV radiation activates star formation in the BRCs.

Key words: infrared: stars — stars: formation — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

1. Introduction

A sequential star-formation process is proposed as one of the major modes of star formation. Bright rimmed clouds (BRCs) are considered to be representative sites of sequential star formation. In these regions, UV radiation from the OB stars ionizes molecular cloud materials through shock. The radiation compresses the cloud, and next-generation stars are subsequently formed. This compression mechanism is known as radiative-driven implosion (Elmegreen & Lada 1977). BRCs are associated with an H II region and an embedded IRAS point source. Sugitani, Fukui, and Ogura (1991) and Sugitani and Ogura (1994) presented a comprehensive catalog of BRCs, in which 89 BRCs are listed. The properties of the clouds have been extensively investigated through centimeter, millimeter, and sub-millimeter observations (de Vries et al. 2002; Morgan et al. 2004, 2008, 2009). Niwa et al. (2009) noticed that molecular clouds facing an H II region show a steep density gradient toward the H II region. They suggested that the BRCs and the H II regions were interacting. Taken together, these studies suggest that triggered star formation was occurring in the clouds.

The products of the cloud compression (i.e., newly forming stars) were also investigated through observations in the optical and infrared wavelengths. Ogura, Sugitani, and Pickles (2002) conducted Hα grism spectroscopy and optical narrow-band imaging observations of 28 BRCs. They detected 460 Hα emission stars in the immediate vicinities of BRCs. The spatial distribution of the stars implies small-scale sequential star formation. Sugitani, Tamura, and Ogura (1995) carried out a near-infrared imaging survey of 44 BRCs, and found small clusters of near-infrared sources in some BRCs. Stars with bluer colors were located closer to the exciting star and those with redder colors were closer to the IRAS sources. They claimed that this variation in color with position implied that star formation propagated from the side of the exciting star to the IRAS position. Matsuyanagi et al. (2006) presented distinct observational evidence for sequential star formation in the BRC 14 region. BRC 14 is one of the most prominent BRCs. The bright rim of BRC 14 is an ionized boundary layer between the hot ionized gas of the H II region IC 1848 (S 199) and the cold dense material of the molecular cloud in which a bright infrared source, AFGL 4029, is embedded. They examined three values as indicators of star formation: the fraction of YSO candidates, the extinctions of all sources, and the near-infrared excesses of the YSO candidates. All indicators increased from the outside of the rim to the center of the molecular cloud. These results indicated that the formation of the low-mass stars in the BRC 14 region proceeds from the outside to the center of the cloud.

We conducted a wide-field deep near-infrared survey of 32 BRCs. The first extensive lists of the near-infrared YSO candidates associated with the BRCs are presented in this paper.

2. Observations and Data Reduction

Wide-field near-infrared imaging observations were carried out on 2009 October 15 with the Wide Field Infrared Camera (WFCam) mounted on the United Kingdom Infrared Telescope (UKIRT). WFCam has four $2048 \times 2048$ HgCdTe detectors, with each detector covering $13.65 \times 13.65$ with a pixel scale of 0′′.4 per pixel. We pointed the telescope as large area of the H II region is observed, thus, the BRC was fixed in the most distant detector from the exciting star. On that detector, the IRAS
source associated with the BRC was pointed at the center. The targets were the 32 BRCs listed in Sugitani, Fukui, and Ogura (1991) and Sugitani and Ogura (1994) that were observable on the observing date. Note that UKIRT cannot point in the northern sky at declinations larger than 60°. Sixteen frames of 5 s exposure each were obtained for the $J$- and $H$-bands, and 16 frames of an 8 s exposure for the $K$-band. We dithered the telescope with 5" width for every exposure. The typical seeing size was 0.8. Dark frames were taken just prior to the object frames.

Data were processed with the pipeline prepared by the Cambridge University Astronomical Survey Unit (CASU). The pipeline process includes dark subtraction, flat fielding, sky removal, compensation for image anomalies, dithering, and combining. For photometry, we concentrated on objects in the frames in which the BRCs were taken. We set 1.4 as the radius of the photometric aperture. The magnitudes of the objects were calibrated with 2MASS sources in the pipeline (Hodgkin et al. 2009). However, we found slight mismatches in plots of the background and foreground stars on the $(J - H$, $H - K)$ color–color diagrams. We suspect that the cause of the mismatch is photometric calibration with the 2MASS sources. Bright 2MASS sources are saturated in the WFCam images, and faint sources have large uncertainties in 2MASS photometry. Photometric calibrations with such sources could cause the color mismatches. We selected as “reliable” sources objects that were brighter than 16.0 mag in the WFCam magnitudes, which were identified as “stellar” by the CASU pipeline, and that the position difference between the WFCam coordinates and the 2MASS coordinates was less than 1". For such sources, we compared the magnitudes in the 2MASS catalog with the output magnitudes of the CASU pipeline. We calculated the mean and standard deviations of the magnitude differences, and then applied 3-σ clipping until no additional sources were rejected by the clipping process. We followed this process for each band and each region. The numbers of sources used for this procedure were between 100 and 5000. As a result, we derived 0.001 or 0.09 mag as the offsets between the magnitudes in the 2MASS catalog and the magnitudes calculated by the CASU pipeline. We added these offsets to the CASU magnitudes.

The 10-σ limiting magnitudes were 18.7 mag, 18.0 mag, and 17.7 mag for the $J$, $H$, and $K$-bands, respectively. Our criteria for identifying an object were that the object was detected in all bands with more than 10-σ photometric accuracy, and the object coordinates in all bands were coincident within 0.4. In our results, we concentrated on objects that were classified as “stellar” by the CASU pipeline.

3. Results

$JHK$-composite images of the BRCs are shown in figures 1 (e-figure 1) and e-figures 2–33. Bright rims of the clouds are seen in the near-infrared image of some BRCs. For several clouds, we found nebular emission components in the clouds, most of which were associated with the IRAS sources. We
detected 87738 objects in the 32 fields.

We selected YSO candidates based on their near-infrared excess, originating from a circumstellar envelope and/or disk. Figure 2 (e-figure 33) and e-figures 34–64 show ($J$ – $H$, $H$ – $K$) color–color diagrams of the stellar objects in the BRC regions. We defined three regions in the color–color diagram (Itoh et al. 1996). The “P” region is the region between the reddening lines extending from the loci of main-sequence stars and giants. We used the reddening law of Meyer, Calvet, and Hillenbrand (1997). The objects plotted in this region are interpreted as being main-sequence stars, giants, supergiants, Class III sources, or Class II sources with small...
near-infrared excess. The “D” region, where Class II sources are mainly plotted, is sandwiched between the “P” region and the reddening line projected from the point of \((J - H, H - K) = (1.1, 1.0)\). This point corresponds to the reddest intrinsic color of classical T Tauri stars (CTTSs: Meyer et al. 1997). Redward of the “D” region is the “E” region, in which Class I sources are plotted. We classified YSO candidates with near-infrared excess as objects plotted in the “D” or “E” region.

With this criterion, 2099 sources were identified as YSO candidates (table 1). The coordinates and magnitudes of the candidates are listed in tables 2 (e-table 1) and e-tables 2–31. Many candidates were invisible sources, while some sources were previously identified in optical, near-infrared, or mid-infrared wavelengths. Some YSO candidates (e.g., BRC 30 #24, #105, or BRC 31 #51) have magnitudes that differ by more than 1 magnitude with the associated 2MASS identification. This discrepancy might be attributed to variability of YSOs. The candidates are not uniformly distributed. For 21 BRCs, more than half of the associated YSO candidates are located inside the cloud. The magnitudes of the candidates are between 9.8 mag and 17.5 mag in the \(K\)-band. Evolutionary tracks indicate that their masses range from 0.006 \(M_\odot\) to 2.7 \(M_\odot\), if an age of 10^6 yr is assumed (Baraffe et al. 1998, 2003; Siess et al. 2000).

4. Discussion

4.1. Morphological Type of BRCs and Associated YSOs

Sugitani, Fukui, and Ogura (1991) defined three morphological types for BRCs, based on the rim shape and the length-to-width ratio. A Type A cloud has a moderately curved rim and a Type B cloud has a tightly curved rim. It is also known as an elephant trunk morphology. A Type C cloud has a cometary rim. Numerical simulations indicated an evolutionary sequence of BRCs (Miao et al. 2009). The youngest type is Type A, which evolves into Type B, then Type C. We examined the relationship between the BRC morphologies and the numbers of the associated YSOs. The distances of the BRCs are not uniform, which introduces an observational bias. The YSO candidates associated with the distant BRCs may not be detected due to their faintness. We counted YSO candidates with absolute \(K\)-band magnitudes brighter than 6.3 mag. This magnitude corresponds to an apparent magnitude of 17.7 mag at 1930 pc. Thus, the numbers of the YSO candidates represent a lower limit for the BRCs whose distance is larger than 1930 pc (BRCs 15, 47, and 49). On the other hand, the YSO candidates associated with relatively nearby BRCs may not be detected if they are located far from the cloud. We counted the YSO candidates within the 2.85 pc \times 2.85 pc field centered on the IRAS source. The extent of this field corresponds to the entire field of WFCam for the BRCs at 700 pc.

Figure 3 shows the relationship between the BRC morphology and the number of YSO candidates associated with the cloud. Several Type A clouds have rich populations of YSO candidates, while fewer YSOs are associated with the Type C clouds. This difference seems to be real, but statistical tests do not provide unambiguous results. The hypothesis that the sample of the Type A clouds and that of the Type B clouds were taken from the same distribution is rejected at only about the 50% significance level by the Peto & Prettice generalized Wilcoxon test. This test did not work well on the Type C sample due to the small sample size.

If this difference is real, it may be attributable to evolution in the YSOs. Those objects identified as being YSO candidates show a near-infrared excess, which is caused by a circumstellar disk or an envelope. A statistical study of several star-forming regions indicates that the dissipation timescale of the circumstellar disk is about 6 Myr (Haisch & Lada 2001). Thus, we imagine that many YSOs associated with an old cloud do not show an infrared excess, and near-infrared imaging observations may miss such YSOs. Matsuyanagi et al. (2004) found spatial variations in the infrared excesses of YSOs associated with BRC 14. YSOs with a large near-infrared excess are located inside the cloud, while YSOs with small near-infrared excess are outside the cloud. They considered that this spatial variation can be attributed to the evolution of the YSOs. We expect that clouds of different ages may harbor YSOs in different phases of evolution. Miao et al. (2009) developed numerical simulations of the morphological evolution of BRCs. They found that the evolutionary timescale from the Type A cloud to the Type C cloud is a few 10^5 yr. This timescale is one order of magnitude shorter than the dissipation timescale of a circumstellar disk around a solar-mass YSO. However, the evolutionary timescale of a BRC depends significantly on the initial conditions and environment of the cloud. A simulation indicated that the evolutionary timescale to Type C is on the order of 1 Myr, given different initial conditions for the molecular cloud (e.g., \(T = 100\) K). If the evolutionary timescale of BRCs from Type A to Type C is on the order of 10^6 yr, the scarcity of the YSOs associated with Type C...
BRCs could be attributed to the evolution of the YSOs. Otherwise, the dependence of the YSO number on the BRC type may be attributable to the evolution of the clouds. Based on simulations of Miao et al. (2009), a less-massive cloud evolves rapidly into a Type C cloud. We suggest that Type A clouds were originally massive clouds that formed many YSOs, whereas Type B and C clouds were originally less massive clouds in which small numbers of YSOs were born.

With a near-infrared imaging survey alone, we could not determine whether the difference in the numbers of the YSO candidates between the types of the BRCs is attributable to the evolution of YSOs or the evolution of clouds. If the evolution of the YSOs makes the difference, optical spectroscopic surveys will find numerous YSO populations with little near-infrared excesses outside the evolved clouds. Also, if the evolution of the clouds makes the difference, dating of the clouds by chemical composition will reveal any coevality of different types of BRCs, instead of the age sequence of BRCs.

4.2. Ultra-Violet Radiation and Star Formation Activity

The star-formation efficiency \( M_{\text{stars}}/(M_{\text{gas}} + M_{\text{stars}}) \) is a fundamental parameter of the star-formation process. By compiling various measurements, Lada and Lada (2003) found that the star-formation efficiencies are about 10% to 30% for nearby star-forming regions. Jørgensen et al. (2008) investigated the star-formation activities of the \( \rho \) Ophiuchus cloud and the Perseus cloud with JCMT/SCUBA sub-millimeter maps and Spitzer archival data. They claimed that the core star-formation efficiencies are 10%–30% for both regions. For BRCs, Morgan et al. (2008) observed 44 BRCs with SCUBA, and detected sub-millimeter continuum emissions from 42 dense cores. If the star-formation process in BRCs is similar to that of nearby molecular clouds, we can imagine that massive BRCs have many YSOs. However, the number of YSOs is not correlated with the core mass (figure 4). The correlation coefficient is 0.89 for all data, but it decreases to 0.007 if BRC 30 is omitted. We conclude that star formation in BRCs is not controlled by the mass of the parent molecular cloud. In addition, we have not found any correlation between the number of YSOs and the spectral type of the exciting star.

We examined UV photons illuminating the cloud surface of the BRCs. UV photons from the exciting OB star ionize the external layers of the cloud and compress the cloud. The UV photon flux at the cloud surface is usually calculated from the spectral type of the exciting star and the distance between the exciting star and the cloud surface. In this calculation, a perpendicular geometry (i.e., the geometry that the star-cloud distance is seen in projection in the plane of the sky) is usually assumed. In addition, absorption material between the exciting star and the cloud is usually assumed to be negligible. However, these assumptions are not always valid (Lefloch et al. 2002). Instead, we used the value of the UV photon flux estimated from the observed centimeter radio continuum flux, although the centimeter fluxes were not measured for all BRCs. Centimeter radio continuum emission is free-free emission originating from the ionized boundary layer. Thompson, Urquhart, and White (2004) observed 45 BRCs in the Southern Hemisphere at 3, 6, 13, and 20 cm wavelengths using the Australian Telescope Compact Array. Morgan et al. (2004) obtained 20-cm radio images of 44 BRCs in the Northern Hemisphere from the NVSS radio catalog. In total, continuum emissions associated with the boundary layer were detected for 13 BRCs among the 32 BRCs we observed, whose integrated fluxes range from 1.2 mJy to 345.5 mJy at 20 cm. For an additional 11 BRCs, the upper limits of the flux were estimated, but for the remaining 8 objects, the radio emissions were contaminated by background galaxies. Morgan et al. (2004) and Thompson, Urquhart, and White (2004) calculated the UV photon flux at the cloud surface from the radio continuum flux. They assumed an effective electron temperature of 104 K. The derived fluxes of the UV photons ranged from \( 1.2 \times 10^{4} \text{cm}^{-2} \text{s}^{-1} \) to \( 2.2 \times 10^{4} \text{cm}^{-2} \text{s}^{-1} \).

We compared the number of the YSOs to the amount of UV photon flux. Figure 5 shows the relationship between the number of YSO candidates and the UV photon flux. We found a correlation; specifically, the number of YSOs increases with increasing UV photon flux. The correlation coefficient is 0.99, and it is 0.89 even if BRC 30 is omitted, providing clear evidence that UV radiation activates star formation in the BRCs.

4.3. Comments on Individual Clouds

4.3.1. BRC 15

This cloud is located at 3.6 kpc. The \( K \)-band limiting magnitude of this survey (17.7 mag) corresponds to an absolute magnitude of 4.9 mag. Thus, the number of YSOs detected was discussed as a lower limit in the previous section.

4.3.2. BRC 16

A nebulosity is seen in the \( K \)-band. Its extent is 370', corresponding to 0.7 pc. This is a Herbig–Haro object, HH240–241. Nisini et al. (2002) detected strong \( H_2 \) emission lines and several Fe II forbidden lines in near-infrared wavelengths. The IRAS source is located in the nebulosity.
Ogura, Sugitani, and Pickles (2002) surveyed Hα emission has been detected at the position of the IRAS source. The IRAS source is associated with a Herbig–Haro object, HH 124 (Walsh et al. 1992; Piché et al. 1995). A red nebulosity was detected at the center of the image. It is bright in the \( J \)-band, but faint in the \( K \)-band image. North of the IRAS source, a cluster of red sources was detected. About half of the YSO candidates are located outside the cloud.

4.3.11. BRC 36

An ionized boundary layer between the molecular cloud and the H II region was detected northeast of the region in all bands. It is prominent in the \( K \)-band, but faint in the \( H \)-band. This structure is known as the "elephant trunk."

4.3.12. BRC 37

Ogura, Sugitani, and Pickles (2002) detected a cluster of \( H\alpha \) emission stars at the head of the BRC. Among them, 3 objects were identified as near-infrared sources with cold colors of \( J - K > 1.2 \) mag (Sugitani et al. 1995). These 3 objects were also detected in our survey, but they do not show a near-infrared excess; thus, they are not classified as YSO candidates. Instead, we identified several YSO candidates with near-infrared excess in the BRCs. These were not detected in the optical study (Ogura et al. 2002). The spatial segregation between the \( H\alpha \) emission stars without near-infrared excesses, located at the head of the BRC, and the YSO candidates with near-infrared excesses, which are embedded in the cloud, may...
indicate small-scale sequential star formation.  

4.3.13. BRC 38

This region is also known as IC 1396 N. Several red nebulosities have been found at the center of the image. These jet features, including Herbig–Haro objects HH 593, show H$_2$ line emission (Beltrán et al. 2009). The IRAS source is located within the nebula. A part of the boundary of the molecular cloud is also bright in near-infrared wavelengths. Beltrán et al. (2009) carried out near-infrared J-, H-, and K-band imaging observations to the central region of BRC 38. They found only a few objects exhibiting a near-infrared excess, and no clear signs of source clustering toward the rim. On the other hand, Choudhury, Mookerjea, and Bhatt (2010) detected an enhanced concentration of YSOs closer to the rim. We found many YSO candidates inside the cloud. Neutral color nebulosities have also been found in the northern region.

4.3.14. BRC 47

A nebulosity was detected at the position of the IRAS source. A stellar cluster appears north of the IRAS source ([DBS2003] 8). Messineo et al. (2007) found an O-type star with an ultra-compact H II region Sh 2-307. We carried out a deep, wide-field near-infrared survey of 32 BRCs with WFCam mounted on UKIRT.

5. Conclusions

We carried out a deep, wide-field near-infrared survey of 32 BRCs with WFCam mounted on UKIRT.

1. Given a limiting magnitude of 17.7 mag at the $K$-band, we identified 2099 YSO candidates with near-infrared excesses. This is the largest sample of YSO candidates associated with BRCs provided to date. Their masses range from 0.006 $M_{\odot}$ to 2.7 $M_{\odot}$.

2. Morphologically young BRCs seem to be associated with large numbers of YSO candidates, while evolved BRCs harbor smaller numbers of candidates. We consider that the evolution of the YSOs or the evolution of the molecular cloud may cause this difference.

3. The number of YSO candidates is not correlated with the core masses of the molecular clouds. Instead, we found a correlation between the ionizing photon flux at the cloud surface and the number of YSO candidates, which is clear evidence for triggered star formation.

We are grateful to Chris Davis for observational support. This work is partly supported by the Hayakawa Foundation.

References


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