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## Sequential Formation of Low-Mass Stars in the BRC 14 Region\*

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### Abstract

We carried out a deep near-infrared survey of a bright-rimmed molecular cloud, BRC 14 (IC 1848A). The  $10\sigma$  limiting magnitude of the survey is 17.7 mag at the  $K$ -band. Seventy-four sources are classified as young stellar object (YSO) candidates based on a near-infrared color–color diagram. The faintest YSO candidates may have masses on the order of tenths of the solar mass, assuming an age of 1 Myr. We examined three values as indicators of star formation: fraction of the YSO candidates, extinctions of all sources, and near-infrared excesses of the YSO candidates. All indicators increase from outside of the rim to the center of the molecular cloud, which suggests that the formation of the low-mass stars in the BRC 14 region proceeds from outside to the center of the cloud.

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

### 1. Introduction

Recent analyses of meteorites confirm the presence of Fe isotopes in the early solar nebula (Tachibana, Huss 2003). This fact suggests that the Sun was formed in a high-mass star-forming region that has experienced at least one supernova explosions (Hester et al. 2004). It is important to understand the formation process of low-mass stars in environments under the influence of massive stars.

Bright-rimmed clouds (BRCs) are considered to be such sites located in the peripheries of H II regions excited by massive stars. Sugitani, Tamura, and Ogura (1995) obtained near-infrared (NIR) images of 44 bright-rimmed clouds that harbor IRAS point sources in the SFO catalog (Sugitani et al. 1991). They found that small NIR clusters are situated from the IRAS source toward the tips of some BRCs, but mostly behind their bright rims. This asymmetric distribution of the clusters strongly suggests star-formation propagation from the side of the H II region toward the IRAS source due to UV from massive stars, i.e., small-scale sequential star formation. This idea is further supported by a grism spectroscopic survey of H $\alpha$  emission stars of BRCs (Ogura et al. 2002).

However, the limiting magnitude of Sugitani et al. (1995) was not deep enough to detect sub-solar mass young stellar objects (YSOs). In fact, the detected sources are considered to be mainly YSOs of  $\sim 1\text{--}2 M_{\odot}$  based on their  $K$ -band magnitude. It is necessary to make deeper NIR observations in order to fully reveal the cluster members associated with the BRCs and to examine the details of star formation there.

BRC 14 (IC 1848A) is considered to be one prominent example of such sequential star formation. The bright rim of BRC 14 is an ionization front at the interface between hot

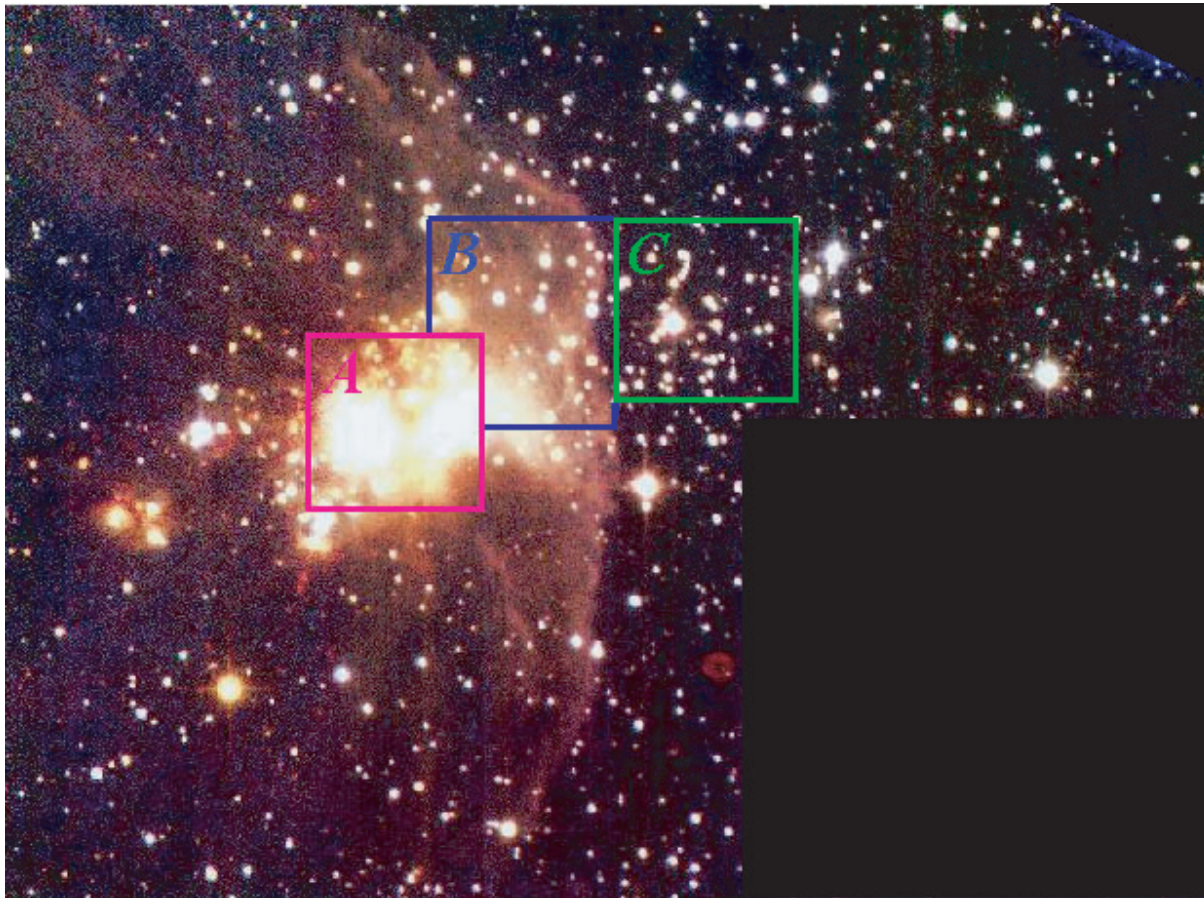
ionized gas of the H II region IC 1848 (S 199) and cold dense material of the molecular cloud, where a bright infrared source, AFGL 4029 (IRAS 02575+6017), is embedded. BRC 14 is a part of an active high-mass star-forming region, IC 1848, whose age is estimated to be  $\leq 1$  Myr (Harris 1976; Feinstein et al. 1986; Deharveng et al. 1997). Its photometric distance is  $2.2 \pm 0.2$  kpc (Becker, Fenkart 1971; Moffat 1972; Deharveng et al. 1997).

Here, we present the results of the deep NIR observations of BRC 14. Based on the photometry of NIR sources, including those of sub-solar masses, we will show clear evidence for sequential star formation of this cloud located in the periphery of IC 1848.

### 2. Observations and Data Reduction

The observations were carried out in 2001 August 26 with the Simultaneous-3 color InfraRed Imager for Unbiased Survey (SIRIUS) mounted on the 2.2 m telescope of University of Hawaii. SIRIUS takes  $JHKs$  images simultaneously using three  $1024 \times 1024$  arrays with a pixel scale of  $0''.288$ . Details of the camera are described in Nagashima et al. (1999) and Nagayama et al. (2003). One quadrant of the  $J$ -band array was not functional at the time of this observation. We imaged a  $4'.9 \times 4'.9$  area centered on  $\alpha = 03^{\text{h}}01^{\text{m}}31^{\text{s}}$ ,  $\delta = +60^{\circ}28'52''$  (J2000), and the same size field with  $-100''$  offset in RA, in order to compensate for any failure of the  $J$ -band array. We obtained 30 dithered images per each area with an exposure time of 30 s for each frame. One part ( $9.8 \text{ arcmin}^2$ ) had twice as much total integration time as the rest. Sky frames, offset  $(\alpha, \delta) = (-120'', +500'')$  from BRC 14, were taken just before and after the object frames. We observed the standard star P 9107 (Persson et al. 1998) for photometric calibration. The typical seeing size was measured to be  $1''.0$  at  $Ks$ . Dome flat frames were obtained at the beginning of the night.

\* The electronic table (E1) is available at the www site of <http://pasj.asj.or.jp/v58/n4/580402/580402-frame.html>.



**Fig. 1.** *JHKs* composite image of BRC 14 (*J* as blue, *H* as green, and *Ks* as red). The field of view is  $6'.6 \times 4'.9$ . North is up and east toward the left. Two luminous sources are AFGL 4029-IRS 1 (west) and IRS 2 (east). The north-south rim is west of AFGL 4029. The extended H II region S 199 is located west (right) of the rim. Three areas (A, B, and C) are shown for discussion. Missing data on the top-right corner and the bottom-right square were caused by failures of the *J*-band array.

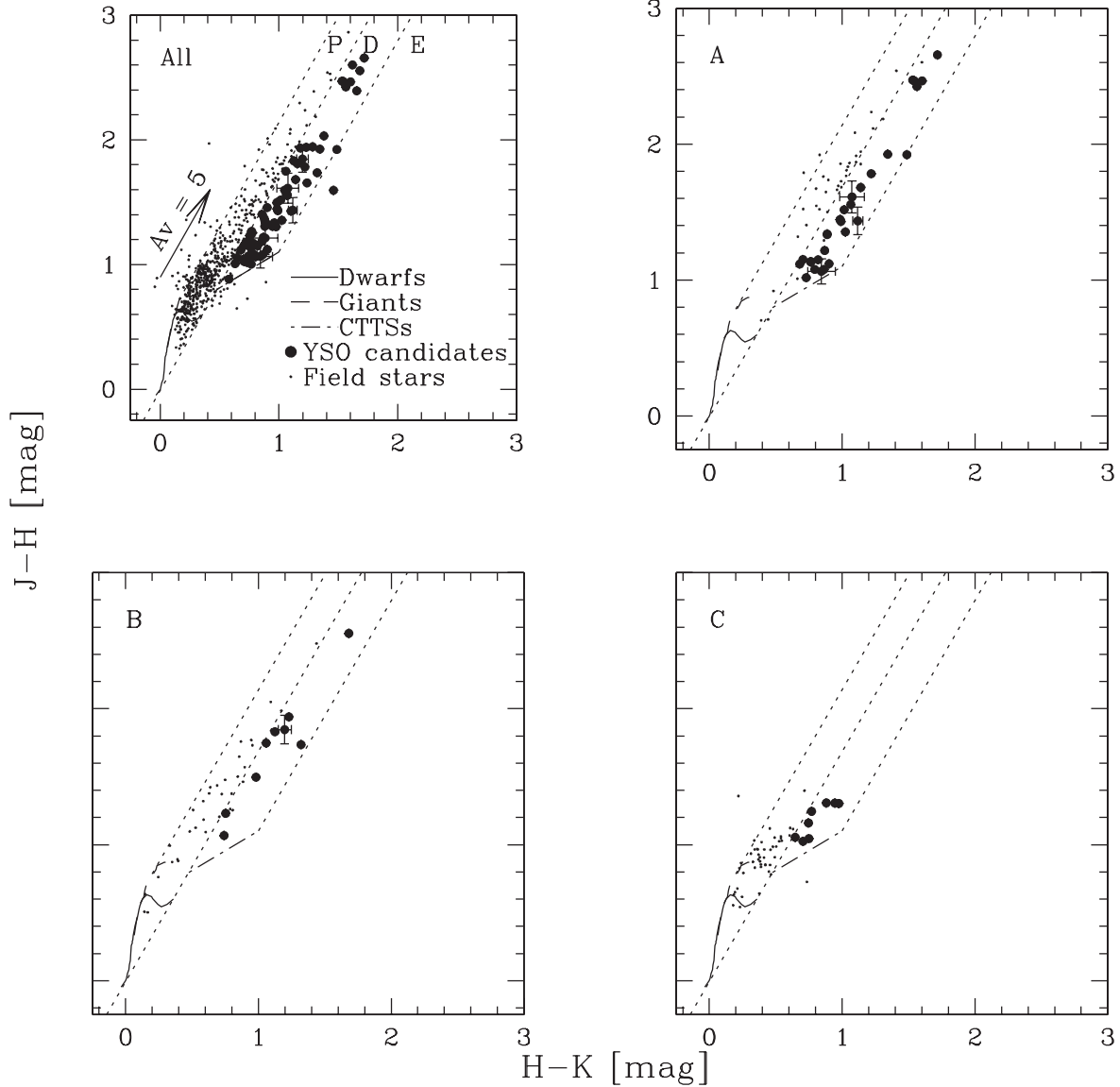
To reduce the data, we used the Imaging Reduction and Analysis Facility (IRAF) software. First, the linearity was corrected for all frames. After subtracting the median-combined sky frame, each image was divided by the normalized flat frame. We then combined them into one frame for each band. To identify NIR sources, we used the DAOFIND task in IRAF with a  $3\sigma$  detection threshold above the background. The APPHOT package was used for photometry with a  $3''.5$  diameter aperture (6 pixel radius). The annular sky area was chosen with an inner radius of  $2''.9$  and an outer radius of  $4''.3$ . All magnitudes were transformed into the CIT *JHK* system. The  $10\sigma$  limiting magnitudes for the photometry are 19.2, 18.5, and 17.7 at the *J*, *H*, and *K* bands, respectively. Bright sources with  $J, H \lesssim 12$ , or  $K \lesssim 11$  were saturated. The coordinates of the objects were determined by three stars listed in the USNO-B1.0 catalog with an accuracy of about  $0''.5$ .

### 3. Results

A *JHKs* composite image of BRC 14 is shown in figure 1. The bright rim of BRC 14 is clearly seen in the NIR image. The position of the NIR rim is coincident with the rim at optical wavelengths. The nebular emission components of

AFGL 4029, IRS 1 (west) and IRS 2 (east), are much brighter in the NIR wavelengths than in the optical wavelengths. Many invisible sources were also detected in the NIR wavelengths. We detected 607 sources within 10% photometric accuracies in all three bands.

We selected YSO candidates based on their NIR excess, originating from a circumstellar envelope and/or disk. The upper-left panel of figure 2 is a  $(J - H, H - K)$  color-color diagram for the entire survey region. 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. The objects plotted in this region are interpreted as main-sequence stars, giants, supergiants, Class III sources, or Class II sources with small NIR 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 NIR-excess (hereafter NIR-YSO candidates) as objects plotted in the “D” or “E” region only if the  $1\sigma$  photometric error bars lie entirely



**Fig. 2.** Color-color diagrams of the objects in the entire region and areas A, B, and C. Only those objects with their photometric uncertainties smaller than 0.1 mag in the three bands are plotted. Error bars are shown in the case of the NIR-YSO candidates with uncertainties  $\geq 0.1$  mag in  $(J-H)$  or  $(H-K)$ . Plotted lines are the intrinsic colors of main-sequence stars, giants (Bessell, Brett 1988), and unreddened CTTs (Meyer et al. 1997). A reddening vector is also shown (Meyer et al. 1997). All colors are transformed into the CIT system. In area A, many sources have large extinctions, and there are a number of NIR-YSO candidates. Extinction in area B is to a similar degree as that in area A, while the NIR-excesses of the YSO candidates are smaller than those in area A. In area C, there are little sources having large extinction, and only the small number of the NIR-YSO candidates are detected.

within those regions.

With this criterion, 74 sources were identified as NIR-YSO candidates (table E1). The objects were identified between the previous NIR observations and our observations, if differences of the position and magnitudes of the object were less than  $0''.5$  and 0.5 mag. No NIR-YSO candidate corresponds to the NIR sources in Deharveng et al. (1997), because most of them are plotted in the “P” (field star) region, and some bright sources are saturated in our observation. Ogura et al. (2002) found 44 emission-line stars in our field of view. Among them, only 10 objects were identified as NIR-YSO candidates by our NIR survey. One reason for this low frequency is that weak-line T Tauri stars have a similar NIR color to

dwarfs. 26 emission-line stars have a weak  $H\alpha$  emission line [ $W(H\alpha) < 10 \text{ \AA}$ ]. The other reason for the low frequency is that even for CTTs half of them cannot be distinguished from field stars only with NIR photometry (Meyer et al. 1997).

#### 4. Discussion

The  $H\alpha$  emission stars are found as an aggregate in the vicinity of the bright rim with an offset toward the exciting stars of S 199 (Ogura et al. 2002). The alignment of the objects from west to east, i.e., the exciting stars, the  $H\alpha$  stars, the bright rim, and AFGL 4029, implies that star formation proceeds from the H II region to AFGL 4029. In order to

**Table 1.** Star-formation indicators for the three areas.

| Area | $A_V$ [mag]* | NIR-YSO fraction <sup>†</sup> | NIR-excess <sup>‡</sup> |
|------|--------------|-------------------------------|-------------------------|
| A    | 8.4 (4.8)    | 29/(65 – 15) (58%)            | 0.41 (0.20)             |
| B    | 6.9 (4.0)    | 9/(42 – 18) (38%)             | 0.29 (0.23)             |
| C    | 3.0 (1.5)    | 8/(56 – 24) (25%)             | 0.29 (0.17)             |

\* Average of the extinctions of all sources and its standard deviation in parentheses.

<sup>†</sup> (the number of the YSO candidates with NIR-excess)/(the number of all sources – the expected number of field stars). Its percentage is shown in parentheses.

<sup>‡</sup> Near-infrared excess of the YSO candidates and its standard deviation in parentheses.

confirm the propagation of star formation, we investigated the characteristics of the YSO candidates in three areas. Each area has about 1' square, as shown in figure 1. Area A, centered on  $(\alpha, \delta) = (03^h01^m33^s, +60^\circ29'19'')$ , contains the luminous source AFGL 4029. Area B is in a bright rim, and is west of area A. Area C is west of the rim. Figure 2 represents color-color diagrams of the objects in the three areas.

We discuss three indicators: extinctions of all sources, fractions of the NIR-YSO candidates, and NIR-excesses of the NIR-YSO candidates (table 1). The average of the extinctions of the sources in the area represents the column density of the molecular cloud. The extinction of each Class II source was derived from the distance between the intrinsic color of the CTTSs and the observed color on the color-color diagram (Meyer et al. 1997). On the other hand, it is difficult to estimate the extinctions of the field-stars. Since we do not know the spectral types of field-stars, we can not distinguish between a late-type dwarf with small extinction and an early-type dwarf with large extinction. A star-count model of the Galaxy (e.g., Jones et al. 1981) predicts that the majority of the field-stars detected by such a deep NIR survey are late-type dwarfs. We assume that the intrinsic color of the field-stars is the line connecting the intrinsic colors of M4 V and K7 V.

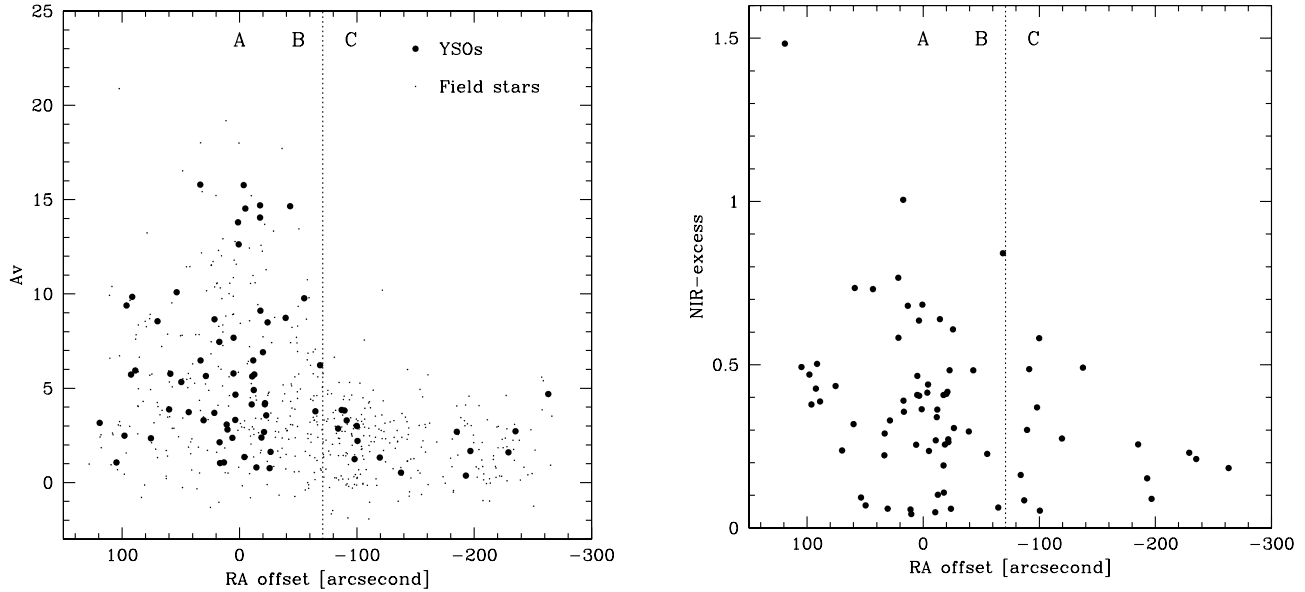
The sources that we detected are categorized into NIR-YSOs, YSO without NIR excess, and field stars. We estimated the number of the field stars in each area. We first counted the 2MASS sources down to  $K < 14$  mag in the region  $(l, b) = (138.3^\circ, -1.56^\circ)$ , the opposite side of the galactic plane. We then calculated the number of the field stars using a star-count model of the Galaxy (Jones et al. 1987). The number of the field stars was overestimated, because the model is valid only for high galactic latitude. The number was well reproduced (difference  $< 5\%$ ) if we took an additional extinction of  $A_K = 0.2$  mag. By extrapolating this model and taking the average extinction in each area, we estimated the number of field star to be 15, 18, and 24 in areas A, B, and C, respectively. The numbers of YSOs were then estimated to be 50, 24, and 32 in areas A, B, and C, respectively. The fraction of NIR-YSO candidates is a ratio of the number of NIR-YSO candidates to the estimated number of YSOs (see table 1). Haisch et al. (2001) analyzed infrared (*JHKL*) colors for several young clusters, and then obtained the relation that the fraction of NIR-YSOs to all YSOs decreases with increasing the age of the cluster.

The NIR-excess index of each YSO candidate was also derived from the color-color diagram. We defined the index as the distance from the color of the object to the boundary between the “P” and “D” regions (the PD boundary), which was then normalized by the distance between the PD boundary and the boundary between the “D” and “E” regions (the DE boundary). An object with an NIR-excess of 0 was plotted on the PD boundary, while that with an NIR-excess of 1 was plotted on the DE boundary. The NIR-excess is a function of many parameters, such as the accretion rate, the inner radius of a disk, and the inclination angle (Hillenbrand et al. 1998). Assuming a random distribution in inclination, we consider that the accretion rate and the inner radius of a disk mainly influence the NIR-excess. As discussed in Oasa et al. (2006), younger YSOs have larger NIR-excesses.

If a cluster is as young as the associated YSOs, which have optically thick disks and are heavily embedded in the parent molecular cloud, all indicators above are expected to be large. In contrast, if a cluster is as old as the YSOs, which do not have optically thick circumstellar disks and are no longer heavily embedded, all indicators should be small. In BRC 14, all indicators decrease in order of areas A, B, and C. Many sources in area A have large extinctions, and area A contains many NIR-YSO candidates. In area B, many sources also have large extinctions, but the fraction of the NIR-YSO candidates as well as the NIR-excesses of the YSO candidates are smaller than those in area A. In area C, the fraction of the NIR-YSO candidates is small, and the sources with large extinctions are less abundant compared to areas A and B. Although these indicators have large uncertainties, all indicators are large for area A and small for area C, implying that area A is young and area C is relatively old. We emphasize that all indicators of area A are significantly larger than those of areas B and C.

The extinctions of all sources and the NIR-excesses of the YSO candidates are also shown as functions of the right ascension of the objects (figure 3). We notice that the extinctions of the sources and the NIR-excesses of the YSO candidates increase toward the east. The extinctions change significantly at the rim. The figures again indicate that the YSOs with circumstellar structures are associated with the molecular cloud. We claim that the sequential star formation previously proposed by an optical study (Ogura et al. 2002) also occurs inside of the rim where NIR light can penetrate.

In all areas, low-mass objects are formed. To make a census of low-mass YSOs in BRC 14, we constructed an extinction-corrected NIR luminosity function of the Class II candidates plotted in the “D” region in the color-color diagram (figure 4). Note that heavily embedded YSO candidates cannot be detected even if their intrinsic luminosity is brighter than the limiting magnitude. To remove this bias of extinction, we consider the *J*-band luminosity function only for the Class II sources with  $A_V \leq 8$  mag. Since  $A_J = 0.288A_V$  (Bessell, Brett 1988),  $A_V = 8$  mag corresponds to  $A_J = 2.3$  mag. The apparent *J*-band limiting magnitude is then 16.9 mag, when we consider the extinction bias. With a distance to BRC 14 of 2.2 kpc, the limiting magnitude in the *J*-band luminosity function is about 5.2 mag in absolute magnitude. By the 1 Myr isochrone of the evolutionary track of low-mass objects (Baraffe et al. 1998), the limiting magnitude corresponds to  $0.12 M_\odot$ . Figure 4

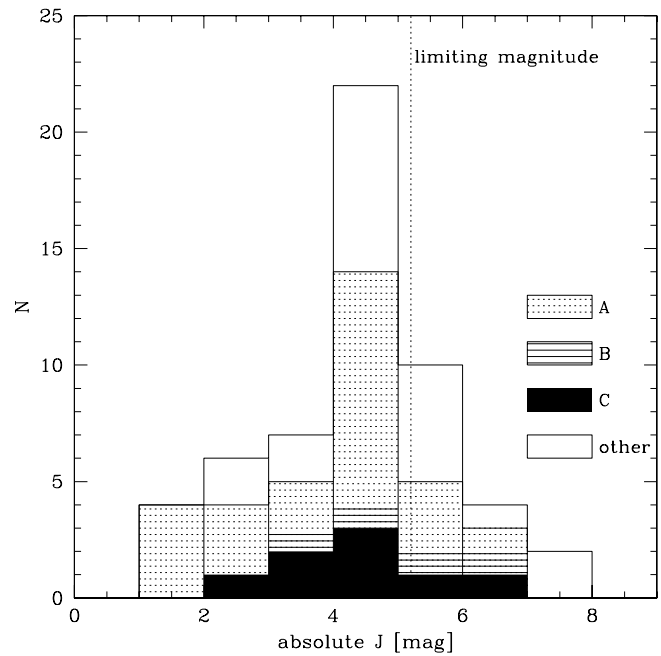


**Fig. 3.** Visual extinctions of all sources and NIR-excesses of the YSO candidates as functions of R.A. R.A. offsets to the center of the area A ( $\alpha = 03^h01^m33^s$ ). The dotted lines are the boundary between areas B and C, representing to the position of the rim. The left region of the boundary corresponds to the direction toward the molecular cloud.

indicates that luminous YSO candidates are located only in area A. They might be younger or massive sources. On the other hand, low-luminosity YSO candidates are found in all three areas.

An aggregate of NIR sources was discovered by Sugitani et al. (1995). Its asymmetric distribution led them to an idea of sequential star formation in the BRC 14 region, though only a qualitative discussion was presented. Ogura et al. (2002) found many H $\alpha$  emission stars in the BRC 14 region. Most of them are located outside of the rim, i.e., in the H II region between the exciting star and the rim. They proposed small-scale sequential star formation from the exciting star to the rim. However, only a small number of emission-line stars were detected inside the rim due to heavy extinction of the cloud. We detected the aggregate of NIR sources inside the rim. By applying the YSO indicators as above, we firstly found quantitative evidence that low-mass stars, including sub-solar mass ones, in BRC 14 sequentially form from the outside of the rim to the inside of the molecular cloud.

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**Fig. 4.** Extinction-corrected  $J$ -band luminosity function of the Class II candidates. The sample is limited to the candidates with  $A_V \leq 8$  mag. The limiting magnitude of the survey is 5.2 mag in the extinction-corrected absolute  $J$ -band magnitude, corresponding to  $0.12 M_{\odot}$ . Low-luminosity YSO candidates are found in all of three areas.

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