TRIGGERED STAR FORMATION IN THE ORION BRIGHT-RIMMED CLOUDS

Hsu-Tai Lee[1]

eridan@astro.ncu.edu.tw

W. P. Chen[1,2]

wchen@astro.ncu.edu.tw

Zhi-Wei Zhang[1]

and

Jing-Yao Hu[3]

ABSTRACT

We have developed an empirical and effective set of criteria, based on the 2MASS colors, to select candidate classical T Tauri stars (CTTS). This provides a useful tool to study the young stellar population in star-forming regions. Here we present our analysis of the bright-rimmed clouds (BRCs) B 35, IC 2118, L 1616, L 1634, and Orion East to show how massive stars interact with molecular clouds to trigger star formation. Our results support the radiation-driven implosion model in which the ionization fronts from OB stars compress a nearby cloud until the density exceeds the critical value, and induce the cloud to collapse to form stars. We find that only BRCs associated with strong IRAS 100 μm emission (tracer of high density) and Hα emission (tracer of ionization front) show signs of ongoing star formation. Relevant timescales, including the ages of O stars, expanding HII regions, and the ages of CTTS, are consistent with sequential star formation. We also find that CTTS are only seen between the OB stars and the BRCs, with those closer to the BRCs progressively younger. There are no CTTS leading the I-fronts, i.e., within the molecular clouds. All these provide strong evidence of triggered star formation and show the major roles massive stars play in sustaining the star-forming activities in the region.

[1]Institute of Astronomy, National Central University, Taiwan 320, R.O.C.

[2]Department of Physics, National Central University, Taiwan, 320, R.O.C.

[3]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People's Republic of China.

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1. INTRODUCTION

Young stars tend to form in clusters or groups. A giant molecular cloud may collapse and fragment to form stars of different masses. The formation of massive stars has an immense impact on the environments. On one hand stellar winds and shock waves from supernova explosion may squeeze molecular clouds and induce subsequent birth of stars which otherwise may not have occurred. On the other hand the perturbation may be so violent as to disperse the material, hindering further star-forming activity. Triggered star formation (see Elmegreen (1998) for a comprehensive review) — as opposed to spontaneous cloud collapse — would have profound consequences in the stellar population, chemical homogeneity, star formation efficiency, and cloud energetics.

While the OB and young low-mass member stars are often distributed cospatially, in some regions, low-mass pre-main-sequence (PMS) stars are seen to locate between the molecular cloud and the cluster. Such a configuration can result from either triggered or spontaneous star formation. High-mass stars first form in dense molecular cores, and then their UV photons create an expanding Strömgren sphere. Such an expanding ionization fronts (I-fronts) would compress nearby molecular clouds and trigger the formation of the next-generation PMS stars at the edge of clouds. Alternatively, star formation may proceed in a spontaneous way; that is, all stars form coevally but high-mass stars photoionize the surrounding clouds and expose the low-mass stars.

The Orion complex is an active star-forming region with a wealth of star-forming signatures, such as high-mass star clusters, OB associations, low-mass young stars, giant molecular clouds, reflection nebulae and HII regions. Because of its proximity, at $\sim$450 pc, it is a suitable laboratory for the study of star formation, especially of the relationship among high-mass stars, low-mass stars and interstellar medium.

Bright-rimmed clouds (BRCs) are usually found at the boundary of HII regions and the edge of molecular clouds. The morphology of a BRC, e.g., tightly curved or cometary rims with tails, is governed by the I-fronts from nearby OB stars, which compress the head of the BRC, hence making the density of the apex higher than the other parts of the cloud. The imprints of such causality offer the possibility to delineate the intricate processes of sequential star formation. Sugitani et al. (1991, 1994) catalogue 89 BRCs with IRAS point sources in both northern and southern hemispheres, and some of the BRCs are also associated with Herbig-Haro objects and molecular outflows. These BRCs are potential sites where triggered star formation might have taken place. Karr & Martin (2003) present a multiwavelength study of triggered star formation in the W5 H II region. They find some young stellar objects around the W5 and suggest the expanding H II region to have induced star formation in the surrounding molecular clouds.

This paper provides observational diagnosis to identify PMS stars from their characteristic near-infrared colors. In particular, PMS stars associated with BRCs in the Orion star-forming region are used as a tool to chronologize the star formation history that shows how massive stars trigger the star formation processes in the region.

We describe in §2 our methodology in selection of the PMS sample in parts of the Orion and Monoceros star-forming regions. In §3 we show the observational results of these PMS stars. In §4 we discuss how our data lend supportive evidence of triggered star formation in the Orion BRCs. The conclusions are summarized in §5.

2. SOURCES OF DATA

Weak-line T Tauri stars (WTTS) are known to emit copious x-ray emission and a majority of them have been identified by optical spectroscopic observations of strong x-ray sources (see Feigelson & Montmerle (1999) for a review). In comparison, classical T Tauri stars (CTTS) are at earlier evolutionary stages, before much of the circumstellar material has been dispersed. CTTS show characteristic strong IR excess emission and Hα emission (equivalent width > 5 Å). The IR excess of CTTS is believed to originate from heated circumstellar dust, and the Hα emission from active chromosphere and the boundary layer between the young star and the fast rotating circumstellar disk. As young stars evolve and gradually clear away the surrounding material, they show different amounts of IR excesses, hence their near-infrared colors (Lada & Adams 1992). Our PMS candidates have been selected on the basis of their infrared colors.

This project started in early 2003, when we used the Two-Micron All-Sky Survey (2MASS) Second Incremental Data Release to identify CTTS candidates in the Orion and Monoceros regions for spectroscopic observations. Since the 2MASS released their All-Sky Data in March 2003, we have updated the photometry of our sample accordingly. The 2MASS database provides unbiased photometry in the near-infrared J (1.25 μm), H (1.65 μm) and K_S (2.17 μm) bands to a limiting 15.8, 15.1, and 14.3 mag., respectively, with a signal-to-noise ratio (SNR) greater than 10. The comprehensive database offers a good opportunity to identify young star candidates associated with molecular clouds. Figure 1 plots the 2MASS $(J-H)$ versus $(H-K_S)$ color-color diagram, in which known young stellar populations, such as the CTTS (Herbig & Bell 1988), WTTS (Wichmann et al. 1996), and Herbig Ae/Be (HAEBE, Thé et al. (1994)) stars, appear to occupy distinguishably different regions. The 2MASS database, with usually simultaneous measurements in all 3 bands, is particularly useful for a diagnostic of young stellar population based on colors, because a majority of PMS stars are variables.

Also shown in Figure 1 is the locus for main sequence stars, for which the WTTS are seen to follow. The CTTS are found to lie approximately between the two parallel dotted lines, defined empirically by $(j\_m - h\_m) - 1.7(h\_m - k\_m) + 0.0976 = 0$ and $(j\_m - h\_m) - 1.7(h\_m - k\_m) + 0.450 = 0$, with the slope determined by the interstellar near-infrared reddening. The dashed line in Figure 1 represents the dereddened CTTS locus (Meyer, Calvet, & Hillenbrand 1997), modified to the 2MASS photometry (Carpenter 2001), with $(j\_m - h\_m) - 0.493(h\_m - k\_m) - 0.439 = 0$. The fact that different kinds of PMS stars occupy separated regions on the $(J - H)$ versus $(H - K_S)$ color-color diagram enables us to identify candidate young stars in star-forming regions. We select 2MASS point sources with colors between the 2 parallel lines and above the dashed line as CTTS candidates. The dotted parallel lines separate CTTS from HAEBE and from reddened main sequence stars. Inevitably our selection would miss some CTTS to the left of the parallel lines, where slightly reddened CTTS and reddened main sequence stars cannot be distinguished by their colors. This poses no limit to our study because our goal is not to collect a complete PMS sample, but to use the young CTTS as probes of the star formation history in the region.

To improve photometry accuracy and remove extended sources from the 2MASS Point Source Catalog, we have set further criteria in selecting our CTTS candidates. These may be useful to other users of the 2MASS data, so we summarize them in Table 1. The Photometric quality flag (ph_qual = AAA) means SNR ≥ 10, and with a corrected photometric uncertainty less than 0.10857, an indication of best quality detection in terms of photometry and astrometry. The Blend flag (bl_flg) = 111 implies no source blending; the Contamination and Confusion flag (cc_flg) = 000 means the source is unaffected by known artifacts, or artifact is not detected in the band. Only sources without a neighboring star within 5 $''$ (prox $> 5.0\ ''$) are considered, so as to avoid possible photometric confusion. We selected only sources which have optical counterparts (a $\neq 0$) and identified CTTS candidates by the near-IR colors prescribed in the last paragraph.

Some slightly extended sources may be included in the 2MASS Point Source Catalog, notably nuclei of galaxies. In order to single out these non-stellar sources, additional criteria have been imposed. An extended source can be discriminated against a point source by the difference between its measured fluxes determined with a point-spread-function (PSF) fitting and with aperture photometry. Conceivably, an extended source measured by PSF photometry would lose some flux at the outer image halo. The 2MASS entries, $[jhk\_m]$, are default magnitudes mostly derived from PSF fitting, whereas the entries, $[jhk\_m\_stdap]$, are standard aperture magnitudes derived from $4''$radius photometric aperture. Therefore the parameter $(j\_m - j\_m\_stdap) + (h\_m - h\_m\_stdap) + (k\_m - k\_m\_stdap)$ should be close to 0 for point sources and significantly non-zero for extended objects. We set $(j\_m - j\_m\_stdap)+(h\_m-h\_m\_stdap)+(k\_m-k\_m\_stdap) \leq 0.3$ as our selection criterion. Finally, we choose sources with signal-to-noise ratios larger than 30 ($[jhk]\_snr > 30$) for high-quality photometry.

The above criteria would bias against sources in crowed regions, but as the end results indicate, proves to lead to high success rate in selection of CTTS candidates.

In addition to the 2MASS data, we also have made use of other survey data, such as the Hα (Finkbeiner 2003), $E(B-V)$ reddening (Schlegel, Finkbeiner, & Davis 1998) and IRAS 100 μm emission in the Orion star-forming region to trace, respectively, the distribution of ionization fronts, cloud extinction and IR radiation with respect to the spatial distribution of our young star sample. This work would concentrate on the star formation in the Orion BRCs, B 30, B 35, Orion East, LDN 1616, LDN 1634, and IC 2118 (Figure 2).

3. SPECTROSCOPIC OBSERVATIONS OF YOUNG STAR CANDIDATES

Table 2 lists the 32 CTTS candidates, selected from the 2MASS Point Source Catalog by the criteria outlined in the last section, for which spectroscopic observations have been carried out to check their young stellar nature. Low-dispersion spectra, with dispersion of 200 Å/mm, 4.8 Å/pixel, were taken with the 2.16 m optical telescope of the Beijing Astronomical Observatory in 22, 23, 30, and 31 January 2003. An OMR (Optomechanics Research Inc.) spectrograph was used with a Tektronix 1024×1024 CCD detector covering 4000-9000 Å. The data were processed with standard NOAO/IRAF packages. After correcting the bias, dark, and flat-fielding, the IRAF package KPNOSLIT was used to extract, and to calibrate the wavelength and flux of each spectrum. The first column of Table 2 gives the sequence number. Columns 2-5 list the 2MASS identification and photometry. Columns 6-9 are, respectively, the spectral type, the associated star-forming region, forbidden line(s) in the spectrum if any, and other names for the source.

Twenty-four of the 32 candidates are found by their spectra to be pre-main sequence stars, with the other 4 as M-type stars and 4 as carbon stars. This indicates that our criteria in selection of PMS stars from the 2MASS database are valid and very effective. The 32 candidates, distributed between RA$\sim$5–6 h covering part of the Orion and part of the Monoceros star-forming regions, were chosen somewhat randomly for spectroscopic observations. All 24 confirmed PMS stars are associated with star-forming regions, but otherwise the M stars and carbon stars are scattered around the region. The high success rate of CTTS selection in nearby molecular clouds, for which both background and foreground field star contamination is minimal, would be conceivably even higher. In the following we thus use PMS candidates to represent the young stellar population in the star-forming regions. We note that stars No. 3, 5, 6, 14, 15, 16, 20, 21, 22 and 24 in Table 2 show continuous or veiled spectra with [OI] and/or [SII] emission lines (Figure 3), characteristics of extreme T Tauri stars for which the forbidden lines originate from jets or winds seen commonly in Class I sources (Kenyon, Brown, Tout, & Berlind 1998).

Figure 4a shows the color-magnitude diagram of the sources in Table 2. The ordinate, the absolute J magnitude, is derived by accepting a distance of 450 pc to Orion clouds and a distance of 830 pc to Mon R2 and LDN 1652 star-forming regions (Maddalena, Moscowitz, Thaddeus, & Morris 1986). One sees that the CTTS with forbidden lines are further away from the zero-age main sequence (ZAMS) than those without forbidden lines, implying that the CTTS with forbidden lines are younger than those without. Figure 4b is the 2MASS color-color diagram for the same sample, in which the CTTS with and without forbidden lines are located respectively at the upper-right and lower-left regions.

This result, that younger CTTS are located at upper-right corner of the IR color-color diagram, is consistent with that obtained by Lada & Adams (1992). The Class I sources have very red colors, $(J - H) > 1.8$, and thus are located at the upper-right corner of the color-color diagram. In contrast, the WTTS are close to the main sequence locus, and the CTTS occupy a region between those of the Class I sources and WTTS. This is understood as an evolutionary sequence, namely a young star evolves from the upper right to the lower left in the near-infrared color-color diagram.

4. EVIDENCE OF TRIGGERED STAR FORMATION

With an effective tool to select PMS stars with different evolutionary status, we are ready to use them to probe the star formation activity and history in a star-forming region. Here we present our analysis of the PMS population in relation with the bright-rimmed molecular clouds and massive stars to investigate how triggered star formation might have taken place. The regions we investigate include the BRCs IC 2118, LDN 1616, and LDN 1634 associated with the Trapezium, Orion East, and B 30 and B 35 associated with the λ Orionis.

IC 2118, LDN 1616 and LDN 1634 are three isolated molecular clouds to the west of the

Orion A, as part of the Orion star-forming region (Figure 1). Each of them is associated with strong IR emission, with bright-rim boundaries clearly outlined by the Hα filaments (Figure 5a and 5b). These 3 molecular clouds are apparently engraved by the UV radiation from the Trapezium, and the Hα filaments are shaped by the I-fronts. The spectra of stars No. 14, 15 and 16, associated with IC 2118 and LDN 1634, all show the forbidden lines [SII] and/or [OI], suggestive of their youth. The spatial distribution of these CTTS likely traces a pre-existent giant molecular cloud complex for which the IC,2118, LDN,1616 and LDN,1634 are merely survivors.

LDN 1621 and LDN 1622, also called the Orion East (Herbig & Rao 1972) are at about the same distance as the Orion B (Maddalena, Moscowitz, Thaddeus, & Morris 1986). Interaction between the Orion East clouds and the I-front can be seen in Figure 6.

B 30 and B 35 are associated with S264, an extended HII region excited by the O8III star λ Orionis, and surrounded by, but slightly off centered of, a ring molecular cloud (Lang, Masheder, Dame, & Thaddeus 2000). Duerr, Imhoff, & Lada (1982) have surveyed about 100 square degrees around λ Orionis, and found 83 Hα emission-line stars, mostly distributed along a bar-like structure extending on either side from λ Orionis to B 30 and B 35. These authors suggest that these Hα stars provide a fossil record of a pre-existent giant molecular cloud complex. Dolan & Mathieu (2002) have identified PMS stars in the region around λ Orionis by statistical removal of field stars in the optical color-magnitude diagram. The seemingly lack of the youngest (1-2 Myr) PMS stars within the molecular ring, despite the apparent abundance of such stars in B 30 and B 35, leads Dolan & Mathieu to suggest a possible supernova explosion near λ Orionis that terminated recent star formation in the vicinity. The CTTS candidates we have identified spread along the bar-like structure, but clearly within the central cavity previous thought to be free of recent star formation activities. Prominent Hα and IRAS 100 μm emission are seen in both B 30 and B 35 on the sides facing λ Orionis (Figure 7a and 7b), signifying the interaction between λ Orionis and these two BRCs.

4.1. COMPARISON WITH THEORY

The radiation-driven implosion (RDI) model, based on the "Rrocket effect", proposed by Oort & Spitzer (1955) and further developed by Bertoldi (1989) and by Bertoldi & McKee (1990), links BRCs to PMSs. The UV photons from massive stars ionize the outer layers of nearby clouds, which expand to interstellar medium with an I-front speed $\sim$ 10 km/s. The expanding I-front plows the cloud material which, when exceeding the critical mass, collapses to form new stars. There are two phases, collapse and cometary, for the formation and evolution of a cometary globule (Lefloch & Lazareff 1994, 1995; Lefloch, Lazareff, & Castets 1997). In the initial collapse phase, the UV photons ionize the surface layers of a cloud, causing the cloud to elongate in the direction of the high-mass stars. This phase lasts some 10^5 yr. Subsequently, the cloud would be in a quasi-stationary state, with small-scale condensations close to critical equilibrium. If the I-front out-pressures the molecular cloud, the pressure will increase to beyond the critical value and the collapse of the condensations will lead to star formation, forming a chain of PMS stars reminiscent of the original, elongated cloud. On the other hand, if the I-front does not out-pressure the molecular gas, the I-front stalls and there should be no star forming. This cometary phase may last a few million to a few 10^7 years. Eventually the entire cometary globule will be evaporated by the UV photons.

According to the RDI model, the surface of BRCs facing the massive stars will be compressed by the I-fronts. De Vries, Narayanan, & Snell (2002) observed B 35 and LDN 1634 in HCO^+ and other molecular line transitions, to trace the swept-up gas ridge and over-dense regions. They find the surfaces of B 35 and LDN 1634 facing the massive stars are indeed being compressed, as the RDI model predicts.

Ogura & Sugitani (1998) listed several dozens of bright-rimmed clouds, cometary globules and reflection clouds in the Orion OB1. They propose these present an evolutionary sequence and collectively call them "remnant molecular clouds". We find that not all remnant molecular clouds are associated with CTTS. Instead, only those BRCs with prominent Hα and IR emission, e.g., IC 2188, LDN 1616, and LDN 1634, have ongoing star formation (Figure 8), consistent with the RDI model. The Hα filaments and the IR emission trace, respectively, the I-fronts and dense regions in a molecular cloud. Obviously in IC 2188, LDN 1616, and LDN 1634, the I-front has out-pressured the molecular cloud and triggered star formation. The two BRCs B 30 and B 35 in the vicinity of Lambda Orionis are additional two such examples of triggered star formation. Remnant clouds without star formation are simply the outcome of I-fronts with insufficient pressure.

The RDI model predicts the cloud to collapse perpendicular to the direction of the ionizing massive stars. This has been observed in LDN 1616 and IC 2118 by Yonekura et al. (1999), for which the ^{12}CO, ^{13}CO, and $C^{18}O$ emission contours show elongation roughly toward the Trapezium.

4.2. SEQUENTIAL STAR FORMATION

Triggered star formation is a sequential process. Massive stars form first, and their I-fronts expand to nearby molecular clouds and cause the second-generation stars to form.

The process may continue until the cloud is consumed and no more star-forming material is available. As time passes, the PMS stars would line up between the massive stars and the molecular cloud, along which the stars farther away from the massive stars, and thus closer to the molecular cloud, should be progressively younger. The youngest stellar objects, namely protostars (Class 0 and Class 1 objects, Lada (1987)), would still be embedded within the cloud.

Our data indicate a systematic brightness difference among revealed CTTS, in the sense that brighter CTTS are more distant from λ Orionis (Figure 7a). We consider this as the consequence of triggered star formation. Initially, the B 30 and B 35 clouds mighty have been more extended toward λ Orionis, perhaps with a bar-like structure (Duerr, Imhoff, & Lada 1982). The I-front from λ Orionis propagates and rams through the clouds, leaving behind newborn stars. Figure 7c is the color-magnitude diagram in the λ Orionis region. Indeed the CTTS closer to B 30 and B 35 are progressively younger, and away from zero-age main sequence. The brightest CTTS, close to B 30 and B 35, may be among the youngest which have just revealed themselves on the birthline and begun their descent down the Hayashi tracks. The same phenomenon, namely the CTTS closer to the BRCs are perceptibly younger, is seen in LDN 1616, LDN 1634 and IC 2118 (Figure 5c). The star formation scenario is thus similar, except there with the Trapezium as the triggering source.

Figure 7d is the color-color diagram in the λ Orionis region. The CTTS physically closer to BRCs are located to the upper-right corner. The extinction values in these BRCs, derived from Schlegel, Finkbeiner, & Davis (1998), are in general too low to affect the apparent colors significantly. This implies these CTTS are intrinsically young. In LDN 1616, LDN 1634 and IC 2118, we also find the same result as in the λ Orionis region (cf. Figure 5d).

Some very young objects are known to exit in these regions, for example Class 0 sources in B 30 (RNO 43MM, Zinnecker, Bastien, Arcoragi, & Yorke (1992)) and in LDN 1616 (L 1616 MMS1A, Stanke, Smith, Gredel, & Szokoly (2002)), and Class I sources in B 35 and in LDN 1634 (De Vries, Narayanan, & Snell 2002). We are apparently witnessing an ongoing star formation sequence, with coexistence of CTTS, younger PMS associated with BRCs, to the youngest protostars within the clouds.

4.3. RELEVANT TIMESCALES

The ages of the concurrent OB stars must be longer than the ages of the second-generation stars plus the I-front traveling time. The stars $^1\theta$ Ori A, B, C, and D, with spectral types B0.5V, B3V, O6:, and B0.5V, respectively (Levato & Abt 1976), are the most massive members in the Trapezium and the main sources to create the I-fronts. The star $^1\theta$ Ori C may be somewhat peculiar in its evolutionary status (Walborn & Panek 1984), so we adopt the age of $^1\theta$Ori A and D, both of spectral type B0.5 V with a lifetime of $6{\times}10^6$ yr (Schaerer & de Koter 1997) to represent the ages of the OB stars.

Assuming IC 2118, LDN 1616 and the Trapezium are at the same distance from us, IC 2118 and LDN 1616 are thus separated from the Trapezium by about 55 pc. With an I-front speed $\sim$ 10 km/s (the sound speed in an HII region), it takes some $5.5{\times}10^6$ yr for the I-front to traverse. The lifetimes of CTTS range from a few 10^5 to a few 10^6 yr. The CTTS associated with the BRCs are younger than those outside the clouds (§4.2), but even for the oldest CTTS in the region, the combined timescale $6{\times}10^6$ yr is consistent with the age of the Trapezium.

The same set of timescales can be estimated for the λ Orionis system, which, rather uniquely, consists of an O star and an HII region surrounded by a molecular cloud ring. The radius of the ring molecular cloud is approximately 2.6 degrees, or about 20 pc at 450 pc distance, so it would take about 2 Myr for the I-front, originated from λ Ori, to travel through the HII region. The age of λ Orionis, an O8III star with a luminosity of 340,000 $L_\odot$ and an effective temperature of 34,700 K (Schmidt-Kaler 1982) can be inferred from evolutionary tracks (Schaerer & de Koter 1997) to be about $3{\times}10^6$ yr. Here again, the age of the triggerer λ Orionis ($3{\times}10^6$ yr) is consistently longer than the expanding timescale of I-front ($2{\times}10^6$ yr) plus the age of CTTS.

4.4. SPATIAL DISTRIBUTION OF CLASSICAL T TAURI STARS

The spatial distribution of CTTS provides telltale evidence of the star formation history in a molecular cloud. If CTTS exist far ahead of the I-front and still embedded in molecular cloud, the star formation must have proceeded in a spontaneous manner, and the embedded CTTS were formed at the same time with their massive counterparts. On the other hand, if CTTS are only seen near the surfaces — and none embedded inside — of BRCs, triggered star formation is clearly evinced. According to the RDI model, small-scale condensations compressed by the I-fronts will reach critical equilibrium first at the surface layers of BRCs, where the CTTS should be found. In B 30, B 35, IC 2118, LDN 1616, and Orion East, CTTS are seen only between the massive stars and BRCs, and on the compressed (i.e., dense) sides of BRCs (Figure 5a, 6 and 7a). No CTTS are found further down behind the compressed regions.

To investigate if the BRCs are indeed void of embedded PMS stars, we have computed the probability of our failure to detect them, if they actually existed, due to excessive dust extinction in the clouds. Table 3 contains the extinction of IC 2118, LDN 1616, LDN 1634, B 30, and B 35 in the Orion region. Column 1 lists the 5 BRCs. Columns 2 to 4 are the $E(B-V)$, A_V, and A_J in each cloud. The values of $E(B-V)$ are derived from Schlegel, Finkbeiner, & Davis (1998), and $R = A_V/E_{B-V} = 3.1$ and $A_J = 0.282 A_V$ (Cox 1999) are used to obtain A_V and A_J . If there were CTTS embedded in a particular cloud, we would like to estimate how many of them would have hidden from our detection. We created the $E(B-V)$ map (Schlegel, Finkbeiner, & Davis 1998) for each cloud, and assumed the same J band luminosity function for the embedded CTTS as that for the visible CTTS outside the cloud. We performed Monte Carlo computation to distribute randomly the hypothetical CTTS stars on the $E(B-V)$ map to check their detectability, given the 2MASS detection limit of $J = 15.0$ based on selection criteria discussed on §2. The probability of non-detection of embedded CTTS in each cloud is given as Column 5. As can be seen, the probability of CTTS that would have escaped our detection is universally very low, < 0.06, implying that the extinction in these clouds is too low to make any embedded PMS invisible. If there were any embedded sources, we would have detected them. We conclude therefore that the CTTS near the surfaces of the BRCs are not part of a young stellar population originally embedded in the molecular clouds, and later revealed by UV photons from massive stars. They have been formed by triggered star formation.

Most PMS stars are associated with molecular clouds, but some are distinctly away from any clouds. These isolated PMS stars, with their juvenility, could not have traversed from the birthplace to their current positions. They are revealed as a consequence of surplus star-forming material being stripped off by radiation and winds from nearby massive stars, leaving behind PMS stars away from molecular clouds.

4.5. HIGH STAR FORMATION EFFICIENCY

Massive stars play a double role in star formation. The I-front compression may induce birth of stars which otherwise may not have formed. Alternatively molecular clouds may become highly perturbed and dispersed, making subsequent star formation impossible. Even if triggered star formation is initiated, the working is confined to the outer layers of the clouds. It is therefore expected that star formation may be efficient in localized, compressed regions, but perhaps not so in the entire cloud. The star formation efficiency in the BRCs can be estimated by the ratio of stellar mass to the total mass of stars plus cloud. De Vries, Narayanan, & Snell (2002) observed the compressed regions of B 35 and LDN 1634 in the HCO^+ molecular line and determined the total compressed mass of molecular clouds to be

27 $M_\odot$ (B 35) and 28 $M_\odot$ (LDN 1634), respectively. We have identified 3 CTTS in each of B 35 and LDN 1634, so assuming 0.5–1 $M_\odot$ for a typical CTTS, the SFEs of the compressed material in B 35 and in LDN 1634 are about 5–10%, higher than that of a few percent ($< 3\%$) in other nearby star-forming regions (White, Casali, & Eiroa 1995).

5. CONCLUSIONS

We have developed an empirical set of criteria to select classical T Tauri candidates on the basis of the infrared colors in the 2MASS Point Source Catalog. Among the 32 candidates we have obtained the spectra, 24 are found to be bona fide PMS objects, 4 are M-type stars and the rest 4 are carbon stars, which shows the effectiveness of our selection method. The young stellar population provides a tool to trace ongoing star formation activities. We find supportive evidence of triggered star formation in the following bright-rimmed clouds, B 35, B 30, IC 2118, LDN 1616, LDN 1634 and Orion East.

1. Our data are consistent with the radiation-driven implosion model that links the formation of BRCs and of stars. The ionization fronts from OB stars compress a nearby cloud, and if the density of the compressed gas exceeds a certain critical value, new stars would be formed. Not all BRCs are associated with CTTS. Only BRCs associated with strong IRAS 100 μm emission (tracer of high density) and Hα emission (tracer of ionization front) show signs of ongoing star formation.

2. Triggered star formation is a sequential process that leads to a configuration in which CTTS closer to BRCs are progressively younger. The brightest CTTS, spatially closest to BRCs, are probably the youngest stellar objects which just reveal themselves on the birthline and begin to descend down the Hayashi tracks.

3. The ages of the concurrent OB stars are comparable or older than the ages of the second-generation stars plus the I-front traveling time. These timescales are consistent with the causality, or sequential, nature of the star formation process.

4. CTTS are found only in between the OB stars and the molecular clouds with which the ionization fronts interact. There are no CTTS ahead of the ionization fronts into the clouds. The lack of embedded young stars cannot be due to detection sensitivity because the extinction of these BRCs is low.

5. Current star formation in the BRCs takes place in the compressed outer layers of the molecular clouds. The relatively enhanced star formation efficiency suggests a triggering—as opposed to a spontaneous—star formation process.

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Fig. 1.— The JHK color-color diagram shows that WTTS (triangles), CTTS (pluses) and HAEBE stars (diamonds) occupy different regions. We select stars located between the 2 parallel lines and above the dashed line as CTTS candidates. The parallel lines separate CTTS from HAEBE stars and reddened main sequence stars The slope of the parallel lines is derived from interstellar reddening.

Fig. 2.— The IRAS 100μm image of the Orion region and the 6 BRCs in this study, B 30, B 35, Orion East, LDN 1616, LDN 1634 and IC 2118.

Fig. 3.— An example CTTS spectrum for star No. 16 shows extreme CTTS characteristics of a veiled continuum with strong Hα, CaII triplets and forbidden [OI] and [SII] lines.

Fig. 4a.—

Fig. 4b.— The color-magnitude diagram (a) and color-color diagram (b) for CTTS with (triangles) and without (crosses) optical forbidden lines. In (a) the solid line represents the ZAMS. In (b) the solid line is the main sequence locus. In either case, the CTTS with forbidden lines are further way from the main sequence, suggestive of their redder colors and younger ages than those without forbidden lines.

Fig. 5a.—

Fig. 5b.—

Fig. 5c.—

Fig. 5d.— ??The (a) IRAS 100 μm image, (b) Hα images, (c) color-magnitude diagram, and (d) color-color diagram in IC 2118, LDN 1616 and LDN,1634. The circles are CTTS physically close to the BRCs, and diamonds are those further way. The 2MASS J magnitude is marked near each star in (a). The solid line in (c) is the ZAMS and in (d) it represents the main sequence locus. The CTTS closer to BRCs are younger.

Fig. 6.— The Hα (left) and IRAS 100 μm (right) images of Orion East, with candidate CTTS marked.

Fig. 7a.—

Fig. 7b.—

Fig. 7c.—

Fig. 7d.— The same as Figure 5 but for B 30 and B 35. Again, CTTS physically closer to BRCs appear to be younger.

Fig. 8.— ??The Hα and IRAS 100μm images of remnant molecular clouds. The white boxes are the remnant molecular clouds in Ogura & Sugitani (1998), and the black dots are the CTTS candidates. We find only those clouds accompanied strong IR and Hα emission associate with CTTS.

Table 1. Selection Criteria of CTTS from 2MASS Point Source Catalog

Criterion	Description
Photometric quality flag (ph_qual) = AAA	$SNR \leq 10$ and $[jhk]\_cmsig < 0.10857$ for best-quality detections in photometry and astrometry
Blend flag (bl_flg) = 111	No source blending
Contamination and confusion flag (cc_flg) = 000	Source unaffected by known artifacts
Proximity (prox) $> 5.0''$	Photometry not confused by nearby objects
Minor Planet Flag (mp_flg) = 0	Not a minor planet
$(j\_m - j\_m\_stdap) + (h\_m - h\_m\_stdap) + (k\_m - k\_m\_stdap) \leq 0.3mag$	To distinguish an extended source from a point source
$(j\_m - h\_m) - 1.7(h\_m - k\_m) + 0.0976 \leq 0$	2MASS colors of CTTS
$(j\_m - h\_m) - 1.7(h\_m - k\_m) + 0.4500 \geq 0$	
$(j\_m - h\_m) - 0.493(h\_m - k\_m) - 0.439 \geq 0$	
Optical counterpart (a) $\neq 0$	With an optical counterpart
signal-to-noise ratio ($[jhk]\_snr$) > 30	SNR > 30

Table 2. Spectroscopic Observations of Young Star Candidates

Star	2MASS	J (mag)	H (mag)	K_S (mag)	Sp. Type[a]	Associated Star Formation Region	Forbidden Line[b]	Other Name
1	J05350900-0427510	10.797	10.109	9.634	K0	Orion A	-	[R2001] 1754
2	J05353672-0510004	13.309	12.481	11.936	M3	Orion A	-	[AD95] 1868
3	J05385149-0801275	12.967	11.525	10.513	M5	Orion A	O, S	
4	J05402496-0755353	12.446	11.367	10.658	M4	Orion A	-	
5	J05412534-0805547	10.604	9.824	9.287	Cont	Orion A	O	HBC 181
6	J05412771-0931414	12.147	11.033	10.272	Cont	Orion A	O	Kiso A-1048 45
7	J05423584-0958552	9.973	8.959	8.227	Cont	Orion A	-	
8	J05432701-0959375	10.984	10.166	9.542	K5	Orion A	-	
9	J05342764-0457051	13.737	12.890	12.286	M2	Orion A	-	[CHS2001] 3990
10	J05342978-0451477	13.241	11.781	10.910	K7	Orion A	-	[CHS2001] 4167
11	J05122053-0255523	10.425	9.688	9.140	K3	-	-	V531 Ori
12	J05371885-0020416	11.577	10.761	10.263	K5	-	-	Kiso A-0904 58
13	J06014515-1413337	11.698	10.896	10.211	K5	-	-	IRAS 05594- 1413
14	J05073016-0610158	10.822	9.572	8.611	M0	IC 2118	O, S	
15	J05073060-0610597	10.120	9.040	8.251	M2	IC 2118	O	
16	J05202573-0547063	11.036	10.202	9.608	Cont	LDN 1634	O, S	V534 Ori
17	J06075243-0516036	10.417	9.474	8.639	K0	Mon R2		HBC 518
18	J06075463-0614342	11.676	10.851	10.094	K0	Mon R2	-	
19	J06080003-0519022	11.384	10.413	9.649	K0	Mon R2	-	
20	J06261259-1028346	12.412	11.352	10.487	Cont	LDN 1652	O, S	
21	J06265529-0958014	11.914	10.901	10.126	Cont	LDN 1652	O	
22	J06265731-0959395	13.161	12.137	11.363	Cont	LDN 1652	O	
23	J06273428-1002397	12.522	11.737	11.176	K7	LDN 1652	-	
24	J06280028-1003420	12.006	10.935	10.091	Cont	LDN 1652	O	
25	J05375005-1548114	6.573	5.571	4.912	M9	-	-	IRAS 05355-1549
26	J06222376-0255509	10.410	8.734	7.559	C	-	-	IRAS 06198-0254
27	J06380179-0557170	8.000	6.711	5.841	C	-	-	
28	J06270654-0540512	8.082	6.751	5.882	C	-	-	
29	J06160006-1727270	10.213	8.978	8.040	C	-	-	
30	J06265037-0738456	9.830	8.845	8.543	M2	-	-	
31	J05345877-0928274	7.700	6.818	6.295	M9	-	-	V653 Ori
32	J05413322-0755022	12.209	11.174	10.526	M2	-	-	Haro 4-488

[a] Count–Continuum with no apparent absorption line(s); C–Carbon star

[b] O–[OI]; S–[SII]

Table 3. EXTINCTION OF BRIGHT-RIMMED CLOUDS

BRC	$E(B-V)^a$ (mag)	$A_V(R=3.1)$ (mag)	A_J (mag)	Nondetection Pro.
IC 2118	1.1–0.2	3.4–0.6	0.96–0.17	0.021
LDN 1616	2.3–0.2	7.1–0.6	2.01–0.17	0.051
LDN 1634	1.1–0.3	3.1–0.9	0.87–0.25	0.013
B 30	2.6–1.5	8.1–4.7	2.28–1.31	0.058
B 35	1.3–0.5	4.0–1.6	1.14–0.44	0.001

[a]Schlegel, Finkbeiner, & Davis (1998)