

DEEP NEAR-INFRARED OBSERVATIONS OF THE X-RAY-EMITTING CLASS 0 PROTOSTAR CANDIDATES IN THE ORION MOLECULAR CLOUD 3¹

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ABSTRACT

We obtained near-infrared (NIR) imaging with the Subaru Telescope of the class 0 protostar candidates in the Orion molecular cloud 3, two of which were discovered to have X-ray emission by the *Chandra X-Ray Observatory*. We found strong evidence for the class 0 nature of the X-ray sources. First, our deep *K*-band image shows no emission brighter than 19.6 mag from both of these X-ray sources. Since class I protostars or class II T Tauri stars should be easily detected in the NIR with this sensitivity, the lack of *K*-band detection suggests that they are likely much more obscured than class I protostars. Second, our H₂ $v = 1-0$ $S(1)$ image shows a bubble-like feature from one of the X-ray class 0 protostar candidates, which reinforces the idea that this is a class 0 protostar. We also discuss the nature of nine NIR sources found in our deep image based on their colors, spatial coincidence with millimeter cores, and the properties of their X-ray counterparts.

Subject headings: infrared: stars — ISM: individual (OMC-3) — stars: pre-main sequence — X-rays: stars

1. INTRODUCTION

Extensive mapping observations at various wavelengths have been performed in the Orion molecular clouds 2 and 3 (hereafter OMC-2/3) in the search for protostars. Chini et al. (1997) detected a chain of 21 cores (MMS 1–MMS 10 in OMC-3, FIR 1a–FIR 6d in OMC-2) at 1.3 mm using the Institut de Radio Astronomie Millimétrique (IRAM) telescope. Combining the James Clerk Maxwell Telescope (JCMT) photometry from 350 μm to 2 mm and the *Infrared Astronomical Satellite* (IRAS) photometry from 12 to 100 μm , they showed that the submillimeter luminosity (L_{submm}) of most cores dominates the bolometric luminosity (L_{bol}). Reipurth, Rodríguez, & Chini (1999) observed the same region at 3.6 cm using the Very Large Array (VLA) and reported the detection of eight 1.3 mm cores. Lis et al. (1998) discovered more than 30 cores (CSO 1–CSO 33) in OMC-2/3 at 350 μm and found that all but one of the 1.3 mm cores have counterparts in 350 μm . Johnstone & Bally (1999) obtained images of this region in 450 and 850 μm . Further, Yu, Bally, & Devine (1997) studied this region with H₂ $v = 1-0$ $S(1)$ (hereafter H₂) emission line and found that about half of the 1.3 mm cores are associated with H₂ jets.

Aso et al. (2000) found that some cores are also accompanied by CO and HCO⁺ molecular outflows. All these indicate the existence of protostars, most of which are probably at the class 0 stage.

More astonishing is the detection of hard X-ray emission from two (MMS 2 and MMS 3) of the millimeter cores using the *Chandra X-Ray Observatory* (Tsuboi et al. 2001). Due to the spatial coincidence with millimeter cores and their hard X-ray spectra, Tsuboi et al. (2001) proposed that they are the first candidates of the X-ray emitting class 0 protostars.

Previous radio and near-infrared (NIR) observations indicate the existence of class 0 protostars at MMS 2 and MMS 3. However, their spatial resolution was not high enough to determine which X-ray source coincides with the class 0 protostar, particularly at MMS 2, where there is a cluster of four X-ray sources. Clearly, follow-up observations with much higher spatial resolution, comparable to that of *Chandra* (positional accuracy of $\sim 0''.1$), are needed.

This paper reports the results of high-resolution NIR imaging observations targeting the X-ray sources seen at MMS 2 and MMS 3.

2. OBSERVATIONS

Observations were performed using the Infrared Camera and Spectrograph (IRCS) at the Cassegrain focus of the Subaru Telescope (Tokunaga et al. 1998; Kobayashi et al. 2000). We took three broadband (*J*-, *H*-, and *K*-band) and two narrowband (H₂ and *K*-continuum) images on 2000 November 30 and December 4. The seeing was $\sim 0''.5$ on

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both nights. The J , K , H_2 , and K -continuum exposure times were 600 s each, while the H exposure time was 300 s. IRCS provides a field of view (FOV) of $60'' \times 60''$ with a pixel scale of $0''.058$. With dithering, we covered a $90'' \times 90''$ field encompassing both MMS 2 and MMS 3.

As we had no detection in the J band from two NIR sources at MMS 2, we obtained an additional L' -band image of MMS 2 with NSFCam (Leggett & Denault 1996) at the Cassegrain focus of the Infrared Telescope Facility (IRTF) on 2000 December 23. The seeing was $\sim 1''.0$, and the integration time was 216 s. NSFCam provides a $38'' \times 38''$ FOV with the pixel scale of $0''.148$. With dithering, we obtained a $64'' \times 64''$ field.

The images were reduced following the standard procedures using IRAF;⁴ i.e., dark subtraction, flat-fielding, sky subtraction, bad pixel removal for each frame, and correction for dithering to construct the final image (Fig. 1).

3. RESULTS

3.1. Source Extraction and Photometry of Broadband Images

SExtractor (Bertin & Arnouts 1996) was used for source extraction and photometry. Nine sources (IRS 1–IRS 9) were extracted from the K -band image (Table 1). For each K -band detected source, we performed a $1''.0$ aperture photometry of the J , H , and K bands. We transformed their magnitudes into the CIT system in the following way. Seven sources are listed in the Point Source Catalog of the 2MASS Second Incremental Data Release.⁵ Referring to their J , H , and K_s magnitudes, we derived a linear relation between IRCS and 2MASS magnitudes in each band. We first converted the IRCS magnitudes into 2MASS magnitudes using these relations and then into the CIT system using the formula given in Carpenter (2001).

For the L' -band image with NSFCam, we performed a $2''.0$ aperture photometry of IRS 3, IRS 4, and IRS 5. We first calculated the magnitudes with the photometric zero point of 20.3 mag⁶ and then converted them into the CIT L -band color⁷ using

$$(K - L)_{\text{CIT}} = 0.820 \times (K - L')_{\text{IRTF}}, \quad (1)$$

where we assume $K_{\text{CIT}} = K_{\text{IRTF}}$ as the first-order approximation.

3.2. Correlation with X-Ray Sources

The X-ray counterpart was searched for each NIR source using the *Chandra* data given in Tsuboi et al. (2001). From the visual inspection of the NIR and X-ray images, the X-ray sources 6, 7, 2, 12, and 3 in Tsuboi et al. (2001; hereafter TKH 6, TKH 7, TKH 2, TKH 12, and TKH 3—the rest follow the same rule) were identified to be the counterparts of IRS 1, IRS 4, IRS 6, IRS 8, and IRS 9, respectively.

Two NIR sources (IRS 3 and IRS 5) and four X-ray sources (TKH 8, TKH 8a, TKH 8b, and TKH 8c) are found at

MMS 2. In order to find the X-ray counterpart of the NIR sources, we adjusted the X-ray image by shift and rotation so that each X-ray source (TKH 2, TKH 3, TKH 6, TKH 7, and TKH 12) comes closest to its NIR counterpart. After this procedure, the positional offset between the NIR sources and their X-ray counterparts is $\sim 0''.25$ rms (1σ).

Then, TKH 8c is found to be the closest source to IRS 5, with a separation of $0''.46$; hence, it is the X-ray counterpart of IRS 5. On the other hand, IRS 3 is separated by $0''.81$ from the closest X-ray source, TKH 8. Assuming that the separation between a NIR and X-ray counterpart pair follows a Gaussian distribution of $\sigma = 0''.25$, the separation between IRS 3 and TKH 8 is more than 3σ . We therefore conclude that TKH 8 is not the X-ray emission from IRS 3. In fact, no separation larger than $0''.81$ is found in any other NIR and X-ray counterpart pairs. TKH 10 at MMS 3, as well as TKH 8 at MMS 2, has no NIR counterpart.

We chose several source-free regions near the positions of TKH 8 and TKH 10 for a $1''.0$ aperture photometry in order to estimate the 1σ level of the background. We found the K -band upper limit of TKH 8 and TKH 10 to be ~ 19.6 mag at the 3σ level.

3.3. Narrowband Images

The vibrational-rotational transition of $v = 1-0 S(1)$ works as an effective coolant of the excited hydrogen molecules. Therefore, this emission line serves as a powerful tool to search for jets from a protostar and the position of its powering source (Bally et al. 1993; Hodapp & Ladd 1995). In a continuum-subtracted H_2 -band image, we identified a bubble-like feature originating from MMS 2. A close-up view of this bubble-like emission is shown in Figure 2, where we see the origin of this feature spatially coincides with TKH 8. No similar feature was found for TKH 10 at MMS 3.

4. DISCUSSION

4.1. The Nature of NIR Sources

For the classification of young stellar objects (YSOs), we use the NIR color-color diagram (Lada & Adams 1992). The $J-H/H-K$ diagram is given in Figure 3a. Since IRS 3 and IRS 5 have no positive detection in the J band, we also give $H-K/K-L$ diagram in Figure 3b.

In these diagrams, protostars and classical T Tauri stars (CTTSs) are positioned right of the reddening vector, where reddened photospheres by extinction are inaccessible because they have redder colors due to an intense circumstellar disk emission. Thus, they can be discriminated from weak-line T Tauri stars (WTTs). Protostars and CTTSs can be separated from each other based on the amount of extinction. Protostars generally show larger extinction due to their richer circumstellar material than CTTSs.

IRS 3 and IRS 5 are at the very center of a millimeter core (MMS 2) and are located $\sim 1''.34$ (~ 600 AU at the distance of 450 pc) apart from each other (Fig. 1). Together with their large extinction of more than $A_V > 50$ mag and large NIR excess seen in Figure 3b, they are class I protostars, probably comprising a binary system.

IRS 1, IRS 2, and IRS 4 are at the reddening region of the CTTS locus with a moderate extinction of $A_V \sim 30$ mag (Fig. 3a). They are located at the edge of 1.3 mm cores (Fig. 1), thus are most likely to be CTTS.

⁴ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

⁵ Go to <http://www.ipac.caltech.edu/2mass/> for more information.

⁶ Go to <http://irtf.ifa.hawaii.edu/Facility/nsfcam/hist/backgrounds.html> for more detail on this aspect of the project.

⁷ Go to <http://irtf.ifa.hawaii.edu/Facility/nsfcam/hist/color.html>.

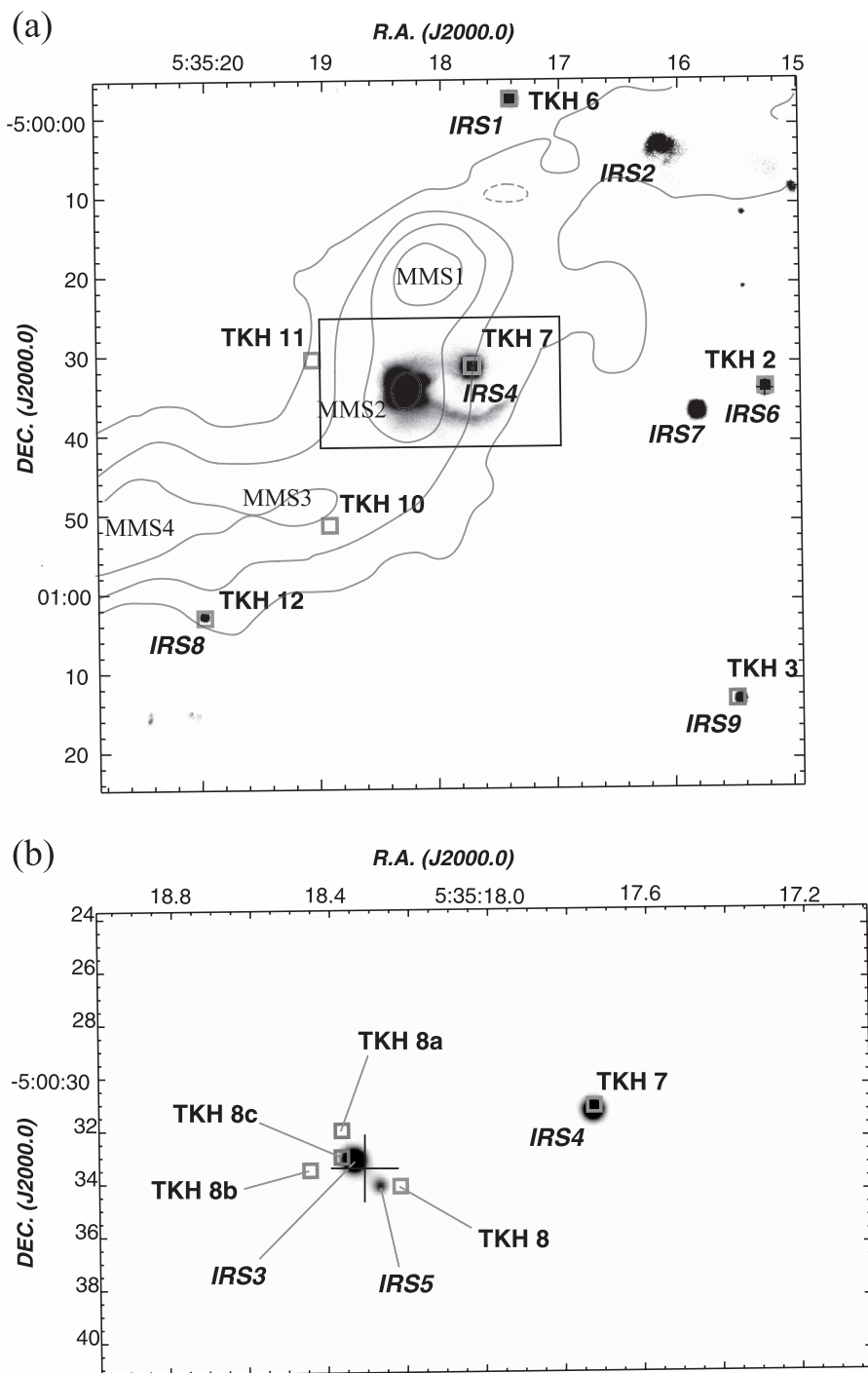


FIG. 1.—(a) IRCS *K*-band image with the logarithmic gray scale to stress diffuse features. (b) Close-up view of the MMS 2 region (*rectangle* in [a]) in the linear scale to show the accurate positions of point sources. *K*-band sources (IRS 1–IRS 9) are labeled in italic, while the positions of the X-ray sources (Tsuboi et al. 2001) are in squares with their names in roman. Contours in (a) are 1.3 mm intensity. Four 1.3 mm cores (MMS 1–MMS 4) were detected in this region (Chini et al. 1997). A cross in (b) shows the position of the 3.6 cm source.

IRS 6, IRS 7, and IRS 9 are located away from the cloud cores (Fig. 1) and have less extinction (Fig. 3a). Among them, IRS 6 and IRS 9 are considered to be WTTS due to the association with X-ray emission. IRS 7, which has no X-ray counterpart, may be a background source.

It is hard to infer the nature of IRS 8 from NIR observation alone because it has only *K*-band detection. However, its X-ray counterpart (TKH 12) shows a thermal emission of $k_B T = 3.2$ keV, $L_X = 5 \times 10^{30}$ ergs s $^{-1}$, and $N_H = 6 \times 10^{22}$ cm $^{-2}$ (Tsuboi et al. 2001). According to Tsujimoto

et al. (2002), who derived a typical X-ray spectrum for protostars (class I), CTTS (class II), and WTTS (class III) in OMC-2/3, TKH 12 (=IRS 8) is most likely to be a class I protostar.

4.2. The X-Ray Emitting Class 0 Protostar Candidates

Class 0 protostars are empirically characterized with the following features (Barsony 1994): (1) undetectable at wavelengths < 10 μ m, (2) a high ratio of $L_{\text{submm}}/L_{\text{bol}}$, (3) a rela-

TABLE 1
THE SOURCE LIST

Name	R.A. ^a	Decl. ^a	J^b (mag)	H^b (mag)	K^b (mag)	L^b (mag)	2MASS Identification	X-Ray ^c Identification
IRS 1.....	05 35 17.415	-04 59 57.24	17.8	14.7	13.0	...	0535174-045957	TKH 6
IRS 2.....	05 35 16.168	-05 00 02.58	17.0	14.1	12.3	...	0535161-050002	...
IRS 3 ^d	05 35 18.275	-05 00 33.93	> 19.6	18.0	13.2	9.17	0535183-050033 ^e	...
IRS 4.....	05 35 17.736	-05 00 31.07	15.4	13.2	11.7	10.5	0535177-050031	TKH 7
IRS 5 ^d	05 35 18.340	-05 00 33.01	> 19.6	15.8	11.4	7.86	0535183-050033 ^e	TKH 8c
IRS 6.....	05 35 15.265	-05 00 33.47	13.3	12.7	12.5	...	0535152-050033	TKH 2
IRS 7.....	05 35 15.837	-05 00 36.34	12.3	11.8	11.7	...	0535158-050036	...
IRS 8.....	05 35 19.980	-05 01 02.64	> 19.6	> 18.8	14.4	...	0535199-050102	TKH 12
IRS 9.....	05 35 15.463	-05 01 12.59	14.2	13.6	13.4	...	0535154-050112	TKH 3

^a The positions are determined from the IRCS K -band image in the equinox J2000.0. Units of right ascension are hours, minutes, and seconds ($0^{\text{h}}0^{\text{m}}0^{\text{s}}$). Units of declination are degrees, arcminutes, and arcseconds ($0^{\circ}0'0''$).

^b All magnitudes are in the CIT system.

^c The X-ray counterpart Tsuboi et al. 2001.

^d Associated with MMS 2.

^e IRS 3 and IRS 5 are not resolved in the 2MASS data.

tively narrow spectral energy distribution, resembling that of a single blackbody of $T \leq 30$ K, (4) the presence of a molecular outflow, and additionally, (5) the existence of cm-wave continuum emission, and (6) the presence of Herbig-Haro (HH) objects.

MMS 2 and MMS 3 were already found to have a high ratio of $L_{\text{submm}}/L_{\text{bol}}$ (Chini et al. 1997). Tsuboi et al. (2001) proposed that hard X-ray sources at MMS 2 and MMS 3 are from class 0 protostars.

With a deep K -band imaging observation, we found that TKH 8 at MMS 2 and TKH 10 at MMS 3 have no NIR emission brighter than ~ 19.6 mag. Class I protostars are generally detected at 10–14 mag and class II T Tauri stars

are at 8–12 mag in the K band at the distance of 450 pc (e.g., see Fig. 24 in Aspin, Sandell, & Russel 1994). Class I and class II stars are therefore easily detected in the NIR with our sensitivity. In fact, two class I protostars at MMS 2 (IRS 3 and IRS 5) show 13.2 and 11.4 mag in the K band. TKH 8 and TKH 10 are fainter than these stars by more than 100 times. This suggests that they are much more obscured than class I protostars, namely at class 0.

A bubble-like emission in H_2 from TKH 8 reinforces this idea. Yu, Bally, & Devine (1997) identified the H_2 emission from MMS 2 in a global scale. MMS 2 is also accompanied by HH objects (Reipurth, Bally, & Devine 1997), molecular outflows (Aso et al. 2000), and 3.6 cm continuum emission

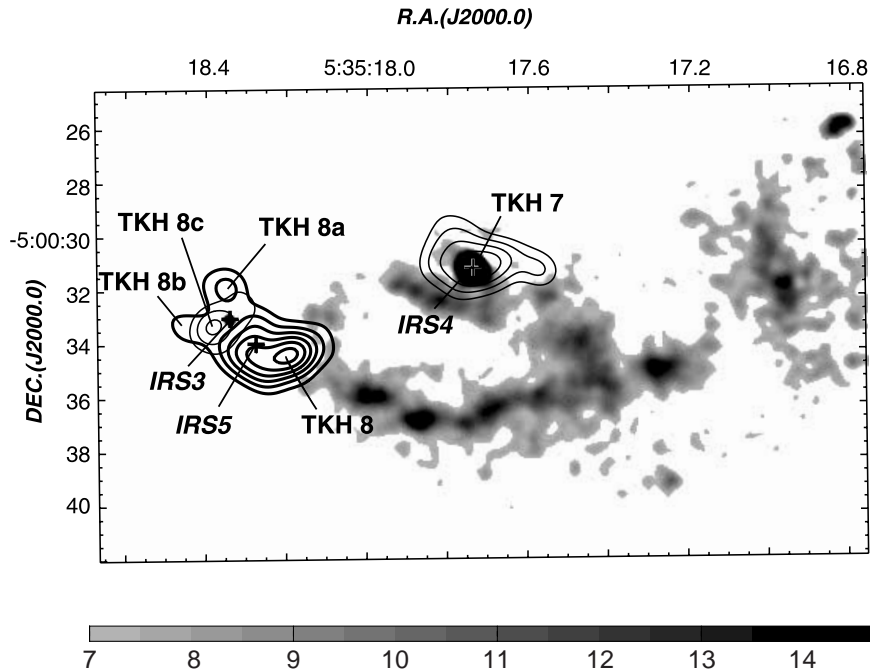


Fig. 2.—Continuum-subtracted H_2 intensity (gray scale) with hard (3.0–6.0 keV) and soft (0.5–3.0 keV) X-ray intensity overlaid with thick and thin contours. The K -continuum image is multiplied by a factor and subtracted from H_2 image, so that the emissions from IRS 3 and IRS 5 cancel out. Without K -continuum subtraction, however, we confirmed the same bubble-like feature in the H_2 image. The scale bar at the bottom is in the unit of intensity pixel^{-1} , where the background level (white) is ~ 2.5 . Crosses: Position of K -band sources. X-ray sources and NIR sources are labeled in roman and italic, respectively.

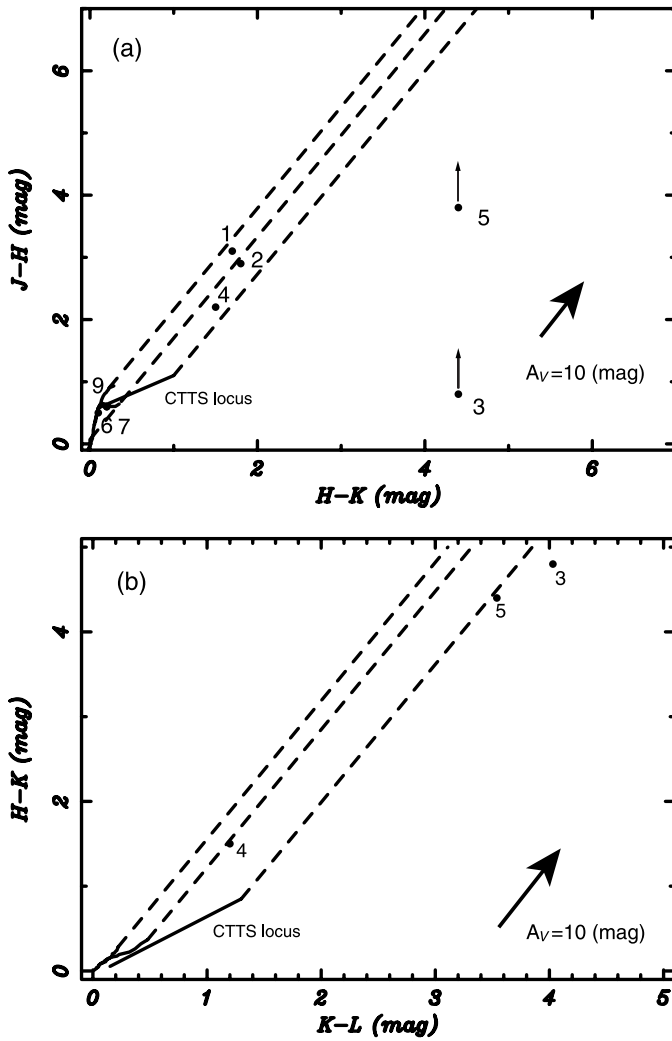


FIG. 3.—(a) $J-H/H-K$ color-color diagram and (b) $H-K/K-L$ color-color diagram. IRS 1–IRS 9 are plotted in the CIT system with the label of their names (“IRS” is omitted). Errors are $\lesssim \pm 0.1$ mag for each color. *Solid lines*: The intrinsic colors of dwarfs and giants (Tokunaga 2000) and the CTTS locus (Meyer, Calvet, & Hillenbrandt 1997). *Dashed lines*: Extinction vectors. We assume the slope of the reddening lines to be $E(J-H)_{\text{reddening}}/E(H-K)_{\text{reddening}} = 1.69$ and $E(H-K)_{\text{reddening}}/E(K-L)_{\text{reddening}} = 1.63$ (Meyer et al. 1997). The A_V of each source is estimated from $E(H-K)_{\text{reddening}} = 0.065 \times A_V$ or $E(K-L)_{\text{reddening}} = 0.04 \times A_V$ (Meyer et al. 1997).

(Reipurth, Rodríguez, & Chini 1999). Our bubble-like feature is at the origin of these jet and outflow phenomena. Therefore, this H_2 emission should be shock-excited by the jet from a protostar. The close-up view of this feature shows that the bubble has a length of $\sim 10''$ ($= 4.5 \times 10^3$ AU) westward away from its central source. This morphology is observed in jets from class 0 protostars (e.g., L 1448 mm and L 1448 IRS 2; Davis et al. 1994; Eisloffel 2000). The well-collimated jet is typical of class 0s, of which the surrounding material is still rich, and the outflow can only go through narrow cavities near the pole (Hodapp 1998). TKH 8, the powering source of the jet, is thus most likely to be the class 0 protostar.

5. SUMMARY

1. In deep NIR imaging of the OMC-3 region, we detected nine K -band sources and derived their J -, H -, and K -band magnitude. We also correlated them with the X-ray sources and found that six sources have the X-ray counterpart.

2. Based on their $J-H$, $H-K$, and $K-L$ colors, spatial coincidence with millimeter cores, and X-ray properties of their X-ray counterparts, we found that three are class I protostars, three are CTTSs, two are WTTSSs, and one is a background source.

3. With a deep K -band image, TKH 8 and TKH 10 were found to have no K -band emission brighter than 19.6 mag, suggesting that they are more highly obscured sources than class I protostars, namely class 0 protostars. With a $H_2 v = 1 - 0 S(1)$ image, a bubble-like feature was found to originate from TKH 8, reinforcing the class 0 nature of this source.

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