

# V1647 Orionis (IRAS 05436–0007): A New Look at McNeil’s Nebula

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## Abstract

We present a study of the newly discovered McNeil’s nebula in Orion using simultaneous observations of the  $JHK_s$ -bands with the near-infrared (NIR) camera SIRIUS on the IRSF 1.4 m telescope. The cometary infrared nebula is clearly seen extending toward both north and south from the NIR source (V1647 Orionis), which illuminates McNeil’s nebula. The compact nebula has an apparent diameter of about  $70''$ . The nebula is blue (bright in  $J$ ) and has a cavity structure with two rims extending toward the north-east and the north-west. The north-east rim is brighter and sharp, while the north-west rim is diffuse. The north-east rim can be traced out to  $\sim 40''$  from the location of the NIR source. In contrast, no cavity structure can be seen toward the south, although the diffuse nebula is extended out to  $\sim 20''$ . New NIR photometric data show a significant variation in the magnitudes ( $> 0.15$  mag) of the source of McNeil’s nebula within a period of one week, which is possibly under the phase of eruptive variables, like FUors or EXors.

**Key words:** ISM: individual (McNeil’s nebula) — reflection nebulae — stars: formation — stars: pre-main-sequence — stars: variables: other

## 1. Introduction

On the night of 2004 January 23, Jay McNeil discovered a new reflection nebula in the L 1630 cloud in Orion (McNeil 2004). His amazing discovery is now recognized as a newly visible reflection nebula surrounding a young star — McNeil’s nebula. McNeil’s new object (V1647 Ori) seems to be a faint optical counterpart to the infrared source catalogued as IRAS 05436–0007 that has gone into outburst, producing a large reflection nebulosity (Reipurth, Aspin 2004; Ábrahám et al. 2004; Briceño et al. 2004; Vacca et al. 2004; Andrews et al. 2004; Walter et al. 2004). Little is known about the source. The discovery was announced by B. Reipurth in Star Formation Newsletter No. 136.<sup>1</sup> Reipurth and Aspin (2004) reported that NIR images taken with the Gemini 8 m telescope show that the object has brightened by about 3 magnitudes in  $JHK$ , relative to the 1998 2MASS measurements. Gemini spectra reveal strong features of CO and Br  $\gamma$  in emission in the IR; in the optical, H $\alpha$  shows emission with a P Cygni profile (Reipurth, Aspin 2004).

McNeil’s source at the apex of the nebula was also observed to brighten dramatically in X-ray and optical wavelengths. The X-ray data from Chandra Observatory gives strong evidence that the probable cause of the outburst is a sudden infall of gas

onto the surface of the star from an orbiting disk of gas (Kastner et al. 2004).

In this letter we present the infrared morphology of McNeil’s nebula as well as infrared monitoring of its central source, especially on a short (about one week) timescale. Both of these pieces of information will be useful to understand the nature of this enigmatic source. We carried out simultaneous  $JHK_s$ -band photometry of McNeil’s nebula during five nights from 2004 February 17 to March 14, and report on a significant variation in the source brightness within a period of one week. These observations also show a new look at McNeil’s nebula in NIR wavelengths. In section 2 we present the details of observations and data-reduction procedures. Section 3 deals with the results and discussion concerning the short time variability of the star that illuminates McNeil’s nebula, and describes the details of infrared nebula. We then summarize our conclusions in section 4.

## 2. Observations and Data Reduction

Imaging observations of McNeil’s nebula region at the NIR wavelengths  $J$  ( $\lambda = 1.25 \mu\text{m}$ ),  $H$  ( $\lambda = 1.65 \mu\text{m}$ ), and  $K_s$  ( $\lambda = 2.15 \mu\text{m}$ ) were obtained on 2004 February 17 (22:00 UT), 23 (18:36 UT), 25 (17:55 UT), 29 (17:48 UT), and 2004 March 14 (17:51 UT) with the Infrared Survey Facility (IRSF) 1.4 m telescope situated at the South African Astronomical

<sup>1</sup> (<http://www.ifa.hawaii.edu/~reipurth/newsletter.htm>).

Observatory, Sutherland, and SIRIUS (Simultaneous three-color InfraRed Imager for Unbiased Surveys), equipped with three  $1024 \times 1024$  HgCdTe arrays. The field of view in each band is  $\sim 7''.7 \times 7''.7$ , with a pixel scale of  $0''.45$ . Further details of the instrument are given in Nagashima et al. (1999) and Nagayama et al. (2003).

For the photometry of the bright NIR source, we obtained 10 dithered exposures of the target centered at  $(\alpha, \delta)_{2000} = (05^{\text{h}}46^{\text{m}}14^{\text{s}}.0, -00^{\circ}05'40''.1)$ , each 1 s long so as to avoid saturation, simultaneously for each band during all four nights. The total on-target integration times in each of the bands were 10 s for photometry of the bright NIR counterpart on all four nights.

We also obtained 10 dithered exposures on 2004 February 17, each 30 s long; 15 dithered exposures on 2004 February 23 and 25, each 10 s long; and 45 dithered exposures each 20 s long on 2004 February 29 and March 14 of the target to study the morphological details of the reflection nebula. The total on-target integration times in each of the bands were 300 s, 150 s, 150 s, 900 s, and 900 s on 2004 February 17, 23, 25, 29, and March 14, respectively.

The observations on 2004 February 23, 25, and 29 were made under good photometric sky conditions. The NIR images were obtained at high airmass ( $\sim 1.9$ ) and under poor seeing conditions ( $\text{FWHM} > 2''$ ) on 2004 February 17; also, the sky condition was not photometric during 2004 March 14. Therefore, we used these observations to study only the morphological details. The average seeing sizes (FWHMs) in all of the bands were  $2''.2$ ,  $1''.6$ ,  $0''.9$ ,  $1''.4$ , and  $0''.9$  on 2004 February 17, 23, 25, 29, and March 14, respectively, during the observations. The observations were made at airmasses of between 1.2 and 1.4 during 2004 February 23–29. Dark frames and twilight flats were obtained at the beginning and end of the observations. A photometric calibration was obtained by observing the standard star 9116 in the faint NIR standard star catalogue of Persson et al. (1998) at air masses closest to the target observations.

Data reduction was done using pipeline software based on NOAO's IRAF<sup>2</sup> package tasks. Twilight flat-fielding and sky subtraction with a median sky frame were applied. Identification and photometry of point sources were performed by using the DAOFIND and DAOPHOT packages in IRAF, respectively. We used an aperture radius of 16 pixels ( $\sim 7''$ ) for photometry of the McNeil's source. The local sky was evaluated in an annulus with an inner radius of 64 pixels and a width of 12 pixels.

### 3. Results and Discussion

#### 3.1. IR Morphology of McNeil's Nebula

Composite color images were constructed from the SIRIUS  $J$ ,  $H$ , and  $K_s$ -band images ( $J$  represented in blue,  $H$  in green, and  $K_s$  in red) obtained under different seeing (FWHMs) conditions, and are shown in figure 1. The lower right panel (figure 1d) shows the  $RHK_s$  ( $R$ : blue,  $H$ : green,  $K_s$ : red)

composite color image of McNeil's nebula after adjusting the spatial resolutions. An  $R$ -band image was acquired using a GMOS-N camera on the Gemini north telescope (Reipurth, Aspin 2004). The cometary infrared nebula is clearly seen extending toward north from the NIR source (see figures 1a, 1b, and 1c). It has a strong morphological resemblance to a ring-shaped nebula, RNO 54, which is associated with an  $H\alpha$ -emission star (Goodrich 1987). McNeil's nebula is blue (bright in  $J$ ) and has a cavity structure with two rims extending toward north-east and north-west. The north-east rim is brighter and sharp, while the north-west rim is diffuse. The north-east rim can be traced out to  $\sim 40''$  or  $\sim 16000$  AU at a surface brightness of  $K_s \sim 18.2$  mag arcsec<sup>-2</sup> (where we assume that the distance to L 1630 is 400 pc; Anthony-Twarog 1982). This kind of morphology can probably be seen when the eruption has cleared out some of the dust and gas in the envelope surrounding the young star, allowing light to escape and to illuminate a cone-shaped cavity carved out by previous eruptions (Reipurth, Aspin 2004). A counter cavity structure is not seen toward the south in our image.

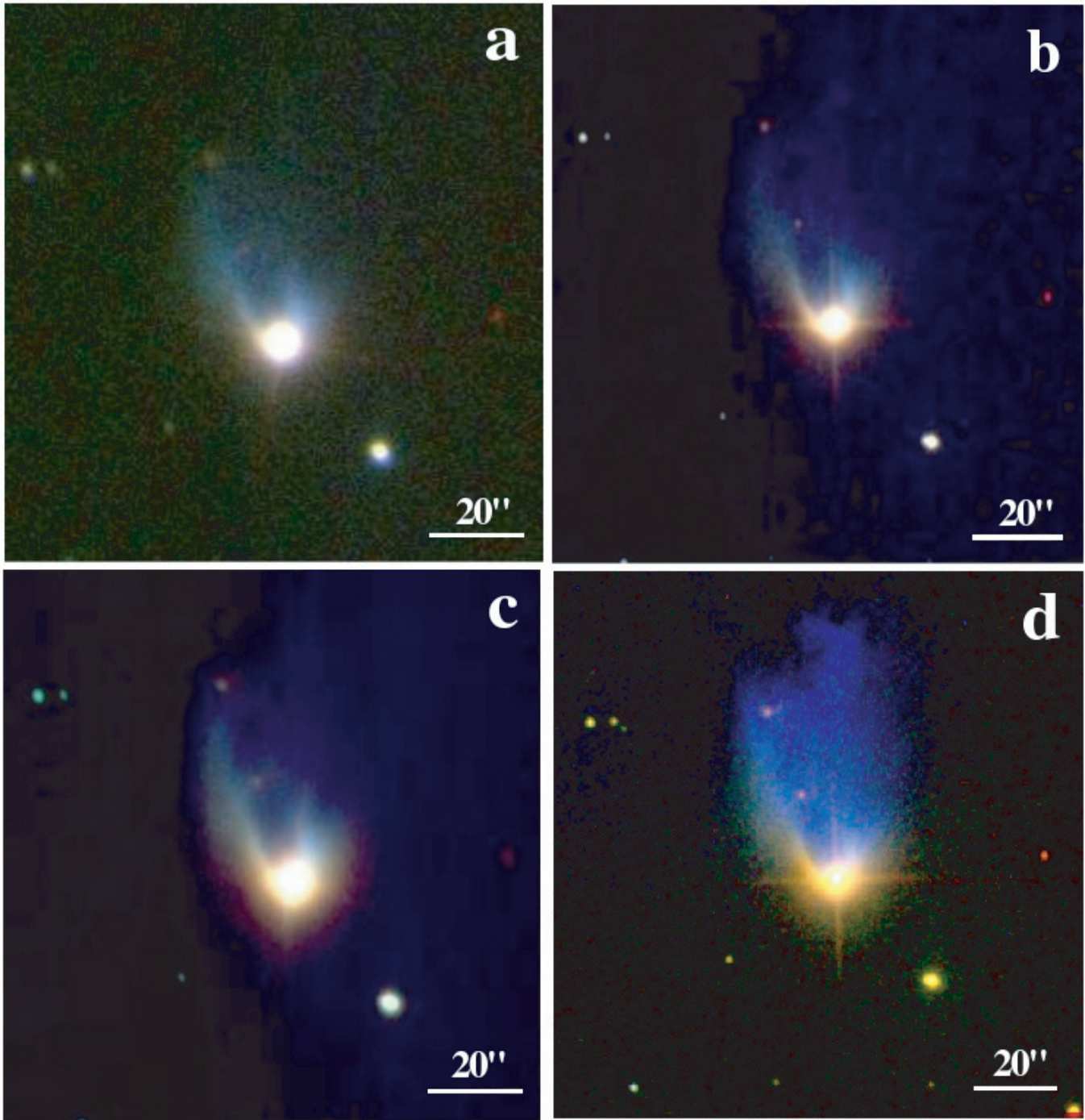
In figure 2 we show a contour diagram of the region around V1647 Ori, as seen in our deep  $K_s$ -band image obtained on 2004 February 29. The star is surrounded by a compact reflection nebulosity that has a curved tail (north-east rim) characteristic (see also Reipurth, Aspin 2004). There is a southward continuation of the extended nebula, which is shown in the PSF-subtracted image of figure 3. This was confirmed by comparing the PSF of the NIR central source, which is a counterpart of the IRAS source with the PSF of the star located about  $30''$  south-west of the IRAS source (figure 3). We thus find that the compact nebula that encloses all of the nebular structure, including the two rims, has an apparent diameter of about  $70''$ .

An IR/optical comparison of the region surrounding McNeil's nebula (see figures 1d and 4) shows that the position of the bright infrared source is coincident with that of an optical source at the apex of the nebula that is illuminating the fan-shaped cloud of gas, or nebula (Reipurth, Aspin 2004). It is interesting to compare the morphology of the optical nebula (see figures 1d, 4 and figure 1 of Reipurth, Aspin 2004) and our IR nebula (figures 1–4). The optical nebula is more widely and predominantly extended to the north, while the IR nebula is relatively confined, but definitely extended, to the south, too. In fact, the IR nebula well matches the reddest parts of the optical nebula. The bluest portion of the optical nebula is not seen in IR including the blue knot HH 22 to the north-east and the blue patch to the north. There is a clear color gradient from north to south, as well as from inside to outside of the cavity. The gradient is very steep near to the central star, and the southern extension of the nebula is seen only at IR. This large color gradient and the sudden absence of an optical nebula to the south is suggestive of a large scale disk-like structure (or envelope) surrounding the central source that hides the southern nebula. This is often the case for YSOs associated with a cometary nebula (e.g., Tamura et al. 1991).

#### 3.2. Short Timescale Variability of the Central IR Source

NIR photometry of McNeil's source obtained on three nights is listed in table 1. A comparison of the  $JHK_s$  magnitudes of

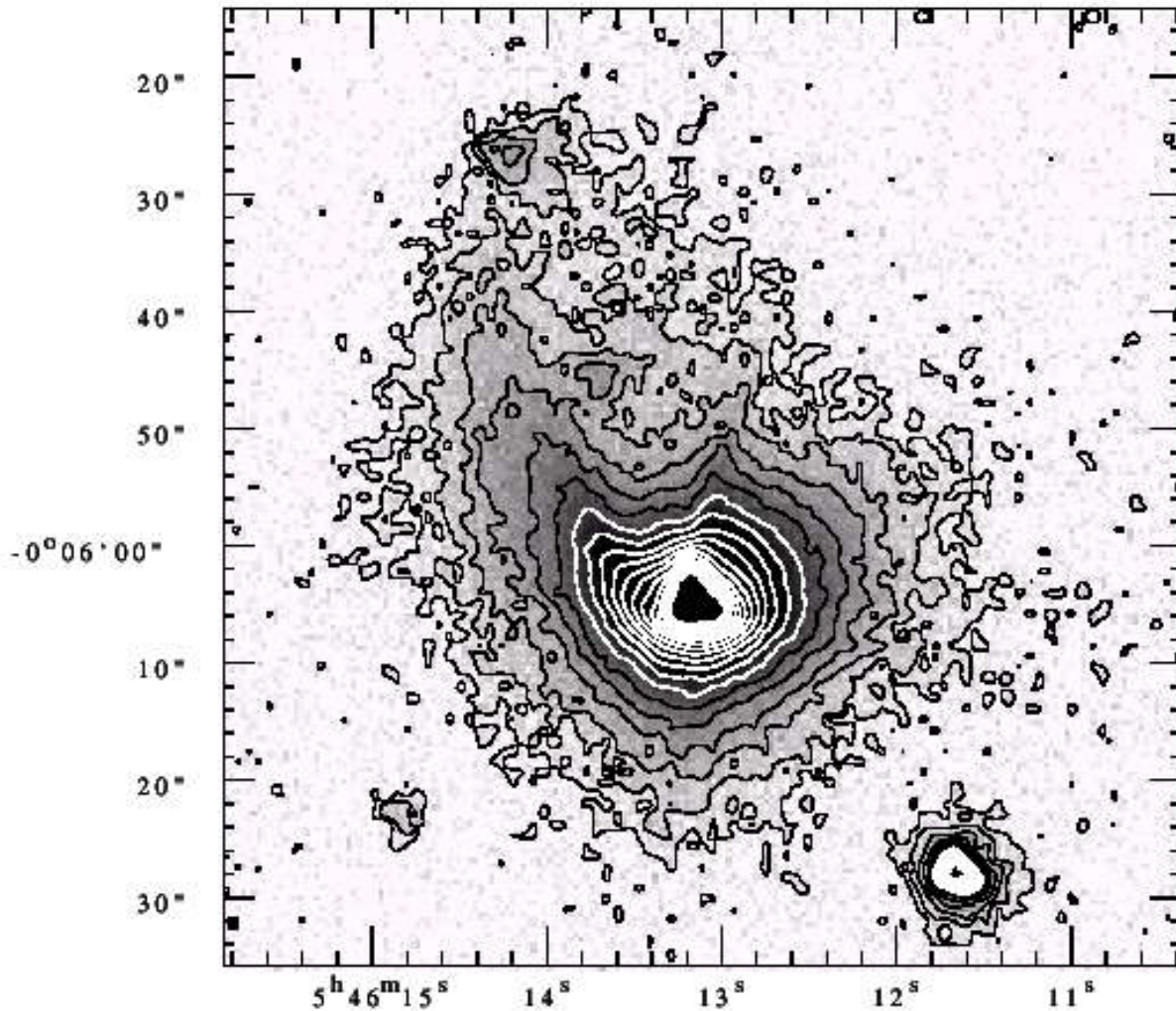
<sup>2</sup> IRAF is distributed by the National Optical Astronomy Observatories, USA, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.



**Fig. 1.**  $JHK_s$  three-color composite images of McNeil's nebula ( $J$ , blue;  $H$ , green;  $K_s$ , red) obtained with SIRIUS mounted on the IRSF 1.4 m telescope on 2004 February 23 [a], February 25 [b] and February 29 [c], respectively. [d]  $RHK_s$  three-color optical/IR composite image ( $R$ , blue;  $H$ , green;  $K_s$ , red) after adjusting the spatial resolutions. The  $R$ -band image was acquired with Gemini on 2004 February 14 (Reipurth, Aspin 2004) and the  $H$  and  $K_s$ -band images were obtained with SIRIUS on 2004 February 25. North is up and east is to the left.

V1647 Ori shows that the source has varied over the time of observation between 2MASS (1998 October) and IRSF (2004 February). Reipurth and Aspin (2004) first showed that the object has become brighter by  $\sim 3$  mag in the  $J$ ,  $H$ , and  $K_s$  bands (table 1). Our photometry is more accurate ( $\Delta m \sim 0.03$ )

than their measurements, although the values are consistent within 0.1 mag error of the Gemini data. We can also see a significant variation in the source brightness ( $\Delta J = 0.16$  mag,  $\Delta H = 0.18$  mag, and  $\Delta K_s = 0.22$  mag) during a period of one week (2004 February 23–29, table 1). Since the difference



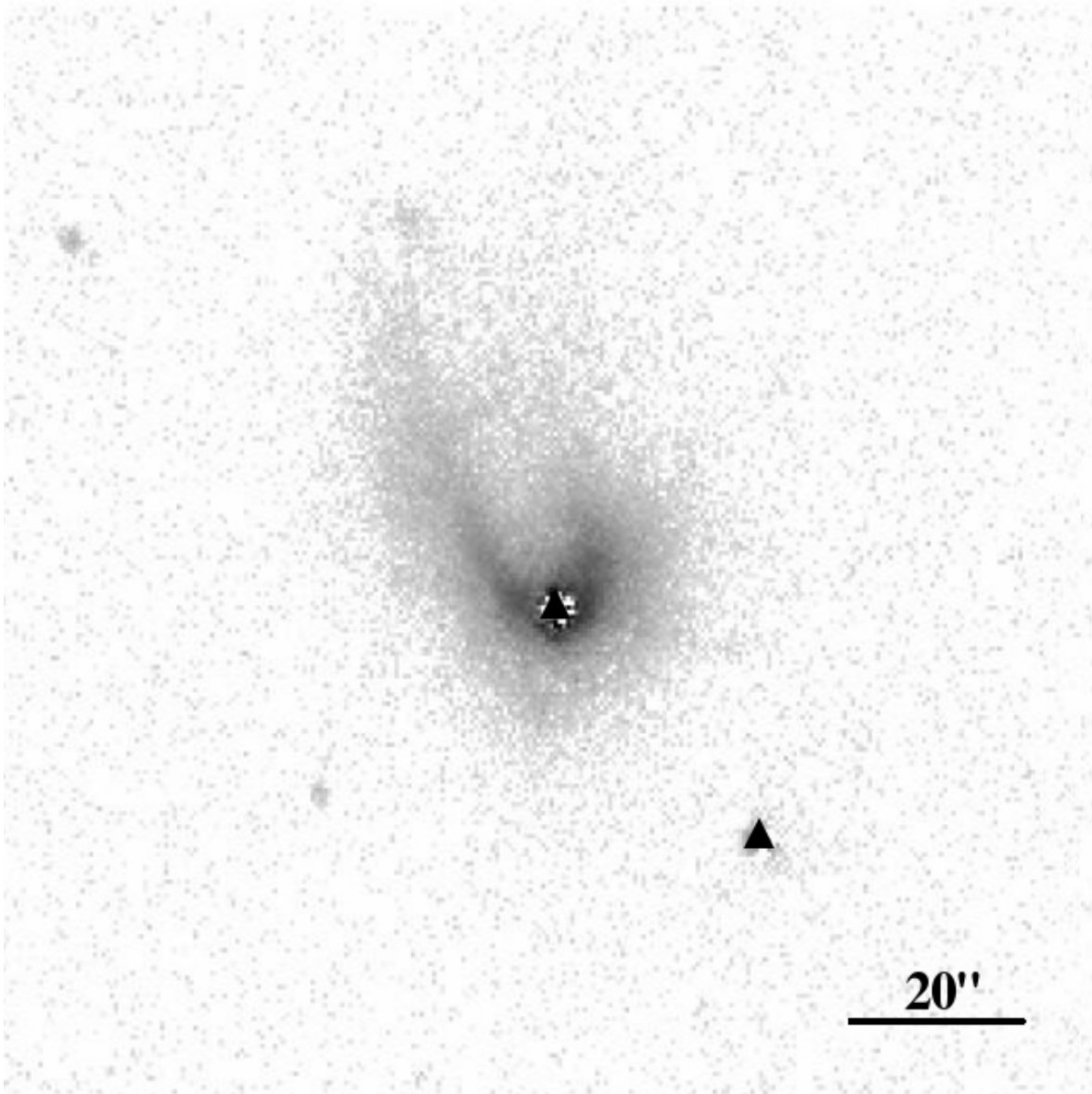
**Fig. 2.** Compact nebula (nebular structure including the two rims) seen around the illuminating star of McNeil's nebula in  $K_s$ -band image obtained on 2004 February 29. The lowest contour and the contour interval are  $18.2 \text{ mag arcsec}^{-2}$  and  $0.3 \text{ mag arcsec}^{-2}$ , respectively. The abscissa and the ordinate are in the J2000 epoch.

in magnitudes is much larger than the photometric errors, we believe that this is real. To examine this, we also did photometry on three bright reference stars in our IR FOV (see table 2). As can be seen in table 2, we can not see a large variation in the magnitudes of the reference stars. This further proves that the brightness variation in V1647 Ori during a period of one week is real. It also shows that the variability is larger at longer wavelengths than shorter ones, and that the brightness decreased by about 0.2 mag in the  $J$ ,  $H$ , and  $K_s$ -bands during 2004 February 23–29 (table 1). Walter et al. (2004) followed the source in optical and NIR wavelengths over 25 nights (2004 February 11–May 7), and also found a general decline in brightness of about 0.3–0.4 magnitudes during these 87 days based on differential light curves. They presented the differential photometry of McNeil's source at NIR wavelengths with respect to the only available comparison star (2MASS 05461162–0006279) in their smaller IR FOV. We also examined this 2MASS source, and found that

the brightness of the 2MASS source is fairly constant during a period of one week (see table 2). Therefore, our observations give an absolute value to McNeil's source variability, and are more reliable.

Figure 5 shows a  $J - H / H - K$  color-color (CC) diagram. For the purpose of plotting the SIRIUS data in a CC diagram, we converted them into the California Institute of Technology (CIT) system using color transformations between the SIRIUS and CIT systems (Y. Nakajima et al., in preparation),<sup>3</sup> which were obtained by observing several of the red standard stars of Persson et al. (1998). We noticed changes of the infrared colors from before (1998) to after the eruption (2004). The star has moved precisely along a reddening vector due to the intrinsic brightening of the star between six years as well as between one week, and is moving toward the tip of the locus of classical

<sup>3</sup> available at ([http://www.z.phys.nagoya-u.ac.jp/~sirius/about/color\\_e.html](http://www.z.phys.nagoya-u.ac.jp/~sirius/about/color_e.html)).

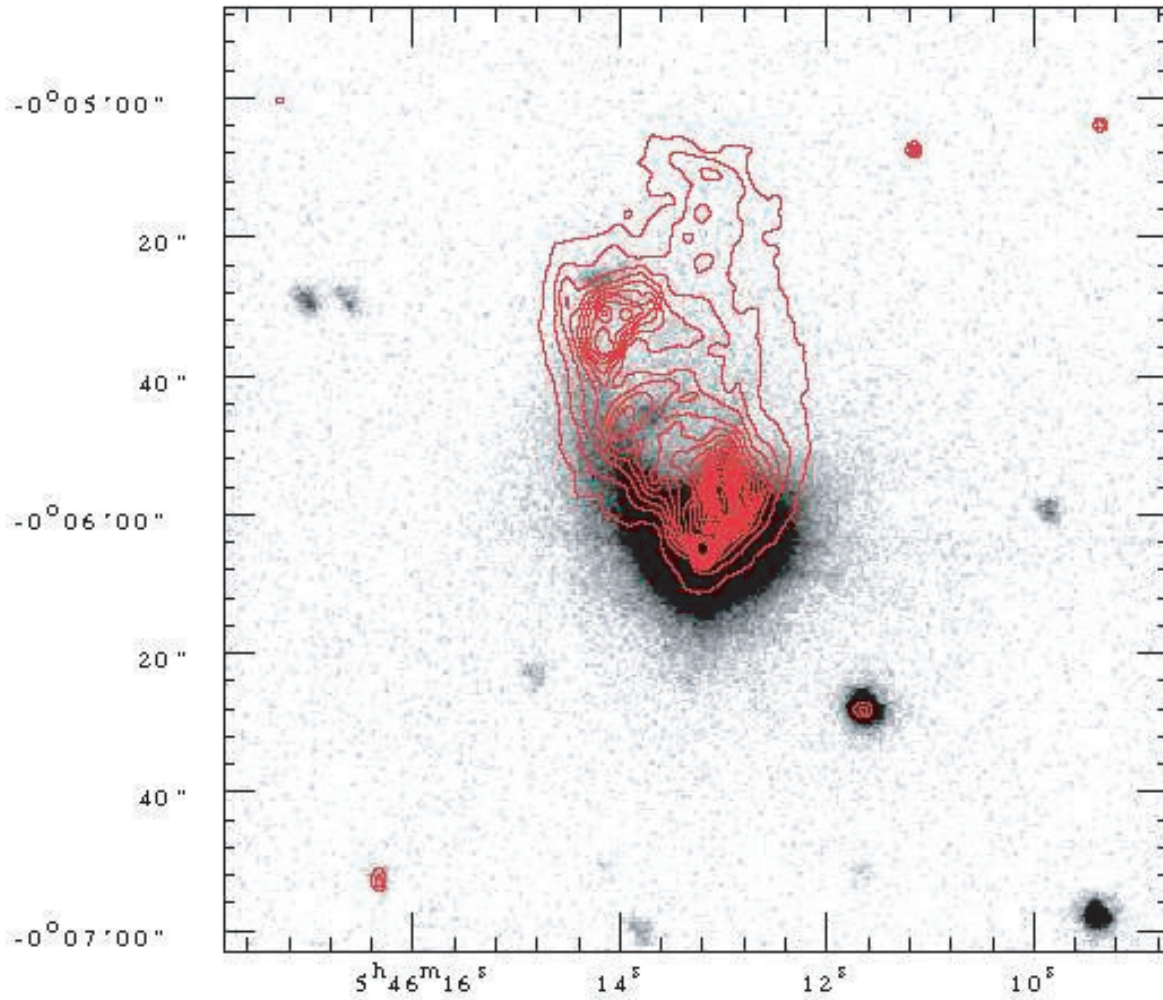


**Fig. 3.** PSF-subtracted image of McNeil's nebula region in the  $H$ -band obtained on 2004 February 23 displayed on a logarithmic intensity scale. North is up and east is to the left. The locations of the NIR central source (V1647 Ori), which is the counterpart of the IRAS source and the star  $\sim 30''$  south-west of V1647 Ori, are indicated by filled triangles in the  $H$ -band image (see the text).

T Tauri stars (Meyer et al. 1997). This suggests that the central source has an NIR color similar to a dereddened T Tauri star. It is to be noted that the seeing is almost the same for data points 1 and 3, but different for point 2 (figure 5 and table 1). Therefore, the comparison between 1 and 3 is more reliable. The  $J - H$  and  $H - K$  values indicate that the circumstellar matter of  $A_V \sim 8$  mag was probably cleared in the eruption, in less than six years since the 2MASS observations. There is still a significant amount ( $A_V \sim 6$  mag) of circumstellar matter if its original colors are assumed to be those of T Tauri stars.

Variability in low-mass YSOs is known (e.g., Hartmann 1998). The total luminosity depends on the mass-accretion rate, and low-mass YSOs like FUor and EXor types of objects have shown variability of several magnitudes at optical and

NIR wavelengths ( $\Delta m \sim 3-4$  mag) (Bell et al. 1995, and references therein). It is possible that we have witnessed an FU Orionis kind of behavior, since the source has about the correct amplitude (Reipurth, Aspin 2004). On the other hand, EXor eruptions, which may occur repeatedly in a given star, have amplitudes that can be comparable to those of FUors, but with much shorter durations (Reipurth, Aspin 2004). Our data show a significant variation in the source brightness within a period of one week (table 1). So far, there have been no infrared data showing such a significant variation within a period of one week or so. Further photometric monitoring of the object is required to settle the class of eruptive variables to which the source of McNeil's nebula belongs.



**Fig. 4.** IR and optical images of the region surrounding McNeil's nebula. SIRIUS  $K_s$ -band image (grey color) obtained on 2004 February 29 is overlaid with contours from the optical  $R$ -band image obtained with Gemini (Reipurth, Aspin 2004). The abscissa and the ordinate are in the J2000 epoch.

**Table 1.**  $JHK$  photometry of McNeil's source (V1647 Ori).

Date (UT)	JD	$J$	$H$	$K_s$	$K'$	$K$	FWHM*	Telescope
1998 Oct 7	...	$14.74 \pm .03$	$12.16 \pm .03$	$10.27 \pm .02$	...	...	...	2MASS
2004 Feb 3	...	$11.1 \pm .1$	$9.0 \pm .1$	...	$7.4 \pm .1$	...	$0''.5$	Gemini <sup>†</sup>
2004 Feb 11	...	$10.79 \pm .01$	$8.83 \pm .01$	...	...	$7.72 \pm .01$	...	USNO <sup>§</sup>
2004 Feb 23 <sup>‡</sup>	2453058.784	$10.74 \pm .05$	$8.93 \pm .01$	$7.40 \pm .02$	...	...	$1''.6$	IRSF
2004 Feb 25 <sup>‡</sup>	2453060.756	$10.79 \pm .05$	$8.95 \pm .01$	$7.47 \pm .01$	...	...	$0''.9$	IRSF
2004 Feb 29 <sup>‡</sup>	2453064.782	$10.90 \pm .06$	$9.11 \pm .01$	$7.62 \pm .02$	...	...	$1''.4$	IRSF
2004 Apr 12	...	$10.94 \pm .02$	$9.06 \pm .02$	...	...	$7.59 \pm .02$	...	USNO <sup>§</sup>

\* Measured FWHM of a standard star. This is a measure of the seeing.

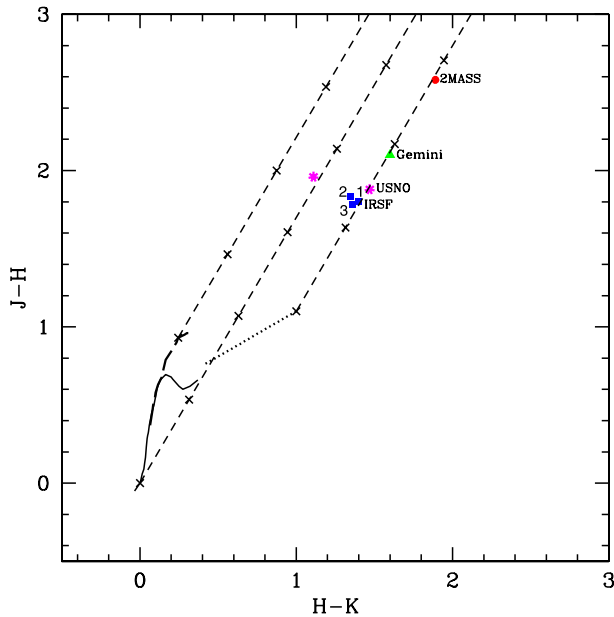
<sup>†</sup> Reipurth and Aspin (2004): photometry is obtained in an aperture with radius  $0''.9$ .

<sup>‡</sup> IRSF photometry is obtained in an aperture with radius  $7''.2$ .

<sup>§</sup> McGehee et al. (2004)

**Table 2.** *JHK* photometry of reference stars at IRSF.

Reference star	<i>J</i>	<i>H</i>	<i>K<sub>s</sub></i>	Date (UT)
2MASS 05461946–0005199	$10.81 \pm .07$	$9.73 \pm .02$	$8.96 \pm .07$	2004 Feb 23
	$10.77 \pm .05$	$9.70 \pm .02$	$8.97 \pm .04$	2004 Feb 29
2MASS 05460575–0002396	$12.34 \pm .02$	$11.27 \pm .01$	$10.82 \pm .02$	2004 Feb 23
	$12.35 \pm .02$	$11.29 \pm .01$	$10.87 \pm .01$	2004 Feb 29
2MASS 05461162–0006279	$13.81 \pm .07$	$12.26 \pm .04$	$11.32 \pm .05$	2004 Feb 23
	$13.80 \pm .07$	$12.27 \pm .02$	$11.33 \pm .02$	2004 Feb 29



**Fig. 5.**  $J - H/H - K$  color-color diagram showing the location of V1647 Ori as observed with 2MASS (filled circle) on 1998 October 7; with IRSF (filled squares) on 2004 February 23 [1], February 25 [2] and February 29 [3]; with Gemini (filled triangle) on 2004 February 3; and with USNO (asterisks) on 2004 February 11 and April 12. The sequences of field dwarfs (solid curve) and giants (thick dashed curve) are from Bessell and Brett (1988). The dotted line represents the locus of T Tauri stars (Meyer et al. 1997). The dashed straight lines represent the reddening vectors (Rieke, Lebofsky 1985). The crosses on the dashed lines are separated by  $A_V = 5$  mag.

#### 4. Conclusions

In this paper we have presented the short time variability and a new look at McNeil’s nebula in NIR wavelengths. We

carried out deep simultaneous NIR observations of McNeil’s nebula during five nights. From an analysis of NIR images, we derive the following conclusions:

- 1) McNeil’s nebula has a cavity structure with two rims, as can be seen in the NIR images. This might have been produced by the eruption that has cleared out a part of the envelope surrounding the young star.
- 2) An IR/optical comparison of McNeil’s nebula shows that the optical nebula is more widely and predominantly extended to the north, while the IR nebula is relatively confined, but definitely extended, to the south, too. This color gradient of the nebula is most likely due to the presence of a large-scale disk around the young star.
- 3) The NIR photometric data show a significant variation in the source brightness ( $> 0.15$  magnitudes) within a period of one week.
- 4) Based on NIR photometry, a post-outburst extinction ( $A_V$ ) to McNeil’s source appears to be about 6 mag, if the intrinsic  $JHK_s$  colors of the central star are the same as that of a T Tauri star.

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#### References

- Ábrahám, P., Kóspál, Á., Csizmadia, Sz., Moór, A., Kun, M., & Stringfellow, G. 2004, *A&A*, 419, L39  
 Andrews, S. M., Rothberg, B., & Simon, T. 2004, *ApJ*, 610, L45  
 Anthony-Twarog, B. J. 1982, *AJ*, 87, 1213  
 Bell, K. R., Lin, D. N. C., Hartmann, L. W., & Kenyon, S. J. 1995, *ApJ*, 444, 376  
 Bessell, M. S., & Brett, J. M. 1988, *PASP*, 100, 1134  
 Briceño, C., et al. 2004, *ApJ*, 606, L123  
 Goodrich, R. W. 1987, *PASP*, 99, 116  
 Hartmann, L. 1998, in *Accretion Processes in Star Formation*, (Cambridge: Cambridge Univ. Press)  
 Kastner, J. H., et al. 2004, *Nature*, 430, 429

- McGehee, P. M., Smith, J. A., Henden, A. A., Richmond, M. W., Knapp, G. R., Finkbeiner, D. P., Ivezić, Ž., & Brinkmann, J. 2004, *ApJ*, 616, 1058
- McNeil, J. W. 2004, *IAU Circ.*, 8284
- Meyer, M. R., Calvet, N., & Hillenbrand, L. A. 1997, *AJ*, 114, 288
- Nagashima, C., et al. 1999, in *Proc. Star Formation 1999*, ed. T. Nakamoto (Nagano: Nobeyama Radio Obs.), 397
- Nagayama, T., et al. 2003, *Proc. SPIE*, 4841, 459
- Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, *AJ*, 116, 2475
- Reipurth, B., & Aspin, C. 2004, *ApJ*, 606, L119
- Rieke, G. H., & Lebofsky, M. J. 1985, *ApJ*, 288, 618
- Tamura, M., Gatley, I., Waller, W., & Werner, M. W. 1991, *ApJ*, 374, L25
- Vacca, W. D., Cushing, M. C., & Simon, T. 2004, *ApJ*, 609, L29
- Walter, F. M., Stringfellow, G. S., Sherry, W. H., & Field-Pollatou, A. 2004, *AJ*, 128, 1872