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Fukagawa, Misato ; Tamura, Motohide ; Suto, Hiroshi ; Itoh, Yoichi ;
Murakawa, Koji ; Oasa, Yumiko ; Hayashi, Saeko S. ; Naoi, Takahiro ;...

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Subaru Near-IR Coronagraphic Image of LkH α 198 *

Misato FUKAGAWA,¹ Motohide TAMURA,² Hiroshi SUTO,³ Yoichi ITOH,⁴
Koji MURAKAWA,³ Yumiko OASA,⁵ Saeko S. HAYASHI,³ Takahiro NAOI,⁶
Norio KAIFU,² and Yoshiyuki DOI³

¹*Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033*
misato@optik.mtk.nao.ac.jp

²*Optical and Infrared Astronomy Division, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588*

³*Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720, USA*

⁴*Graduate School of Science and Technology, Kobe University, 1-1 Rokkodai, Nada, Kobe 657-8501*

⁵*Earth Observation Research Center, National Space Development Agency of Japan, 1-8-10 Harumi, Chuo-ku, Tokyo 104-6023*

⁶*Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033*

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Abstract

High-resolution near-infrared imaging of a Herbig Ae/Be star LkH α 198 has been carried out using the coronagraphic camera CIAO (Coronagraphic Imager with Adaptive Optics) on the Subaru 8.2 m Telescope. Obtained images resolve the infrared companion (IRC) and an associated reflection nebula. The IRC exhibits near-infrared colors suggestive of a class I-like source. Faint nebulae associated with outflow activity and a bright flattened envelope are also found around the primary. Our observations provide morphological evidence of the IRC being an outflow source as well as the primary star.

Key words: infrared: stars — ISM: reflection nebulae — stars: formation

1. Introduction

Herbig Ae/Be stars are pre-main-sequence stars covering a mass range of about 2–10 M_{\odot} (for reviews, see Pérez, Grady 1997; Waters, Waelkens 1998). They are generally recognized to be higher mass analogs of T Tauri stars and the evolutionary precursors of the Vega-like stars, such as β Pic. Despite extensive previous observations, we still have less knowledge about the circumstellar structure of Herbig Ae/Be stars than that of T Tauri stars. Their central stars are too bright and their distances are often too far to resolve faint envelopes, disks, or companions in their close vicinity. Higher-resolution and higher-contrast observations are needed to investigate the circumstellar structures of Herbig Ae/Be stars.

In order to resolve their nearby environments, we initiated a high-resolution coronagraphic imaging survey of Herbig Ae/Be stars in the near-infrared. Coronagraphy is a powerful technique to suppress the halo of the bright central object and to obtain a higher contrast between the faint nearby targets. Our goal is to understand the evolutionary sequence by studying the resolved surroundings around each star. We report in this paper on the observational results of our first target, LkH α 198.

LkH α 198 is classified as a Herbig Ae/Be star (Herbig 1960), located in a small dark cloud, L 1265, at a distance of 600 pc (Chavarría-K 1985). LkH α 198 is a well-studied Herbig Ae/Be star and its complicated environment has been revealed by many observations. Lagage et al. (1993) found a deeply embedded ($A_V > 35$ mag) companion 6'' north of LkH α 198 using mid-infrared observations. Because this companion is

detectable at infrared but not at visible wavelengths, we henceforth refer to it as an infrared companion (IRC). A millimeter source is situated 19'' northwest (Sandell, Weintraub 1994; Hajjar, Bastien 2000) and another Herbig Ae/Be star V376 Cas exists 35'' north of LkH α 198. A number of Herbig–Haro objects (Corcoran et al. 1995) and CO outflows (e.g. Nakano et al. 1990; Sandell, Weintraub 1994) have been observed in the 2' region around LkH α 198. The adjacency of the multiple sources makes it difficult to obtain individual characteristics. The IRC, in particular, is so close to the LkH α 198 primary that the past near-infrared observations only just resolved the companion star in the K and H bands (Corcoran et al. 1995; Koresko et al. 1997). We observed LkH α 198 in order to investigate the nature of the IRC, and to reveal the morphology of the surroundings around both the primary and the IRC on a scale of several arcseconds.

2. Observations and Data Reductions

High-resolution near-infrared images were taken in 2000 October using the Coronagraphic Imager with Adaptive Optics (CIAO, Tamura et al. 2000) mounted at the f/12 Cassegrain focus of the Subaru 8.2 m telescope. CIAO has an occulting mask at the focal plane and a Lyot stop at the pupil plane, both of which are cooled to cryogenic temperatures. The adaptive optics (AO) was not available at the time the observations were made; thus, the observations were conducted without AO with a seeing of 0.''4–0.''6 in the near-infrared. The occulting mask which we used had a diameter of 1.''5. At the medium-resolution-mode of CIAO, the 1024 \times 1024 InSb array (ALADDIN II) gives a scale of 0.''022 pixel⁻¹ and a field of view of 22'' \times 22''. The imaging was carried out in the J , H ,

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

and K bands. The total integration time in each band was 120 s ($10\text{ s} \times 12\text{ frames}$). Just after observing LkH α 198, we imaged HD 224784 as a PSF reference star which was near our target on the sky. The PSF reference star was observed similarly using the $1''.5$ mask, and its total integration time was 72 s in each of the J , H , and K bands.

Individual frames were calibrated as follows: dark subtraction, flat-fielding with dome-flats, and bad-pixel substitution. Aperture photometry was performed for the LkH α 198 IRC using APPHOT package in IRAF. The UKIRT faint standard star FS 104 (Hawarden et al. 2001) was utilized as a photometric calibrator. Although thin cirrus made the photometry less accurate, the magnitudes of the unmasked primary star were in good agreement with those previously measured (Li et al. 1994).

3. Results and Discussion

3.1. Infrared Companion (IRC)

3.1.1. Nebula associated with the IRC

The IRC and its nebula were clearly resolved, as shown in figure 1. This is the first report that the IRC is associated with the parabolic nebula which has an axis along P.A. $\sim 130^\circ$. The parabolic nebula can be interpreted as an infrared reflection nebula associated with an outflow (e.g., Tamura et al. 1991). Besides its parabolic morphology, there is further evidence that the nebula is illuminated by the IRC, itself: polarimetric maps at 900 nm presented by Leinert et al. (1991) and Pirola et al. (1992) show that the position angle of polarization at the east side of the IRC is perpendicular to the elongation of the northern part of the parabolic nebula.

Part of this nebula is also seen in visible light. In their study, Asselin et al. (1996) found features “E, F, G” in their figure 8a. These are reflection nebulosities defining the parabolic nebula of the IRC. “E” is on the northern part of it, and “F, G” on the southern part. Corcoran et al. (1995) also detected an optically visible nebulosity which they referred to as LkH α 198 B situated about $5''$ northeast of LkH α 198. This is the same feature as “E” in Asselin et al. (1996), corresponding to the northern part of the parabolic nebula.

The possibility of the IRC to be an outflow source has been discussed based on whether it is the source of a large elliptical loop nebula extending southeast of LkH α 198 with a scale of $40''$ and P.A. = 130° (Lagage et al. 1993; Corcoran et al. 1995). The previous considerations are based on large-scale geometrical evidence that the IRC is on the axis of the elliptical loop. Our observations provide direct evidence that the IRC is an independent outflow source associated with its own reflection nebula.

The detection of the parabolic nebula strongly suggests that the IRC is the driving source of Herbig–Haro object HH 161 detected by Corcoran et al. (1995) and later Aspin and Reipurth (2000). HH 161 A is situated about $15''$ and at P.A. = 135° from the IRC, and its “tail” structure points to the IRC. Moreover, HH 161 A, B, and the IRC are placed on a single straight line. These observations were most readily accounted for if the IRC was the driving source (Corcoran et al. 1995). In addition, our results indicate that the IRC is an outflow source and the direction of the outflow is about 130° . Therefore, among three possible candidates (the primary, IRC, and millimeter source)

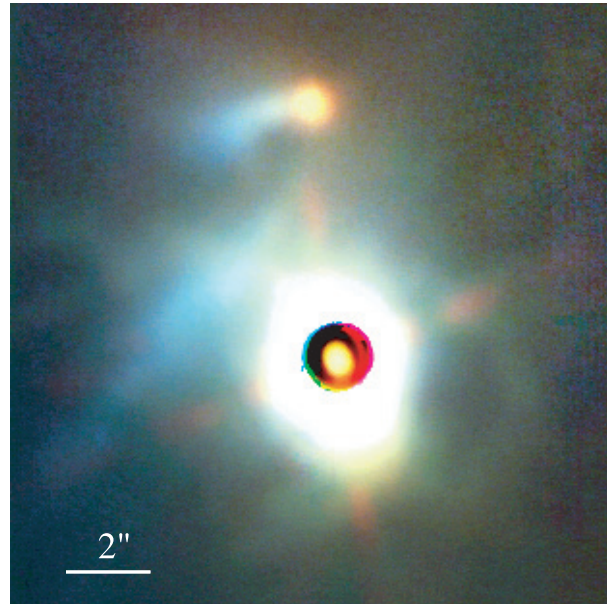


Fig. 1. JHK color composite image of LkH α 198 and its companion. The PSF is not subtracted. The central mask has a diameter of $1''.5$. The peak intensity of LkH α 198 is transmitted through the mask. The faint red cross seen in N–S and NW–SE is the secondary spider pattern. North is up, and east is to the left.

the IRC is most likely to be the exciting source of HH 161.

We measured the positions of the IRC relative to the primary star in each band. The peak position of the primary can be detected because the occulting mask of CIAO has $\sim 2\%$ transmission. Asselin et al. (1996) claimed that there is no positional wavelength-dependence for the primary in the BVR bands. Assuming that the position of the primary does not change with the wavelengths in the JHK bands, the position of the IRC at J moves $0''.15$ east compared with that at K . The positional uncertainties are $0''.07$ and $0''.007$ at J and K , respectively. Moreover, the position at J is $0''.23$ east from the peak position measured at $10\mu\text{m}$ by Lagage et al. (1993). For the north–south direction, the displacement between the JHK bands is negligible within the uncertainties, but $0''.16$ south at JHK relative to the $10\mu\text{m}$ position. This wavelength-dependence is most readily accounted for by a disk around the IRC, whose inclination is nearly edge-on. At shorter wavelength, the apparent position of the stellar component moves to the optically-thinner direction, perpendicular to the disk (e.g., L1551 IRS5; Campbell et al. 1988). The disk of the IRC is expected to tilt as its north-west side is forward and the southeast side is backward. This interpretation is consistent with the unipolar morphology of the parabolic reflection nebula which extends to the southeast, as shown in figure 1.

Figure 2 presents a line profile of the IRC including the northern part of the parabolic nebula in the east–west direction. The profiles in the J and H bands are asymmetric about the position of the peak intensity, broader in the east side than in the west. This is consistent with the view of the disk hiding the west side of the IRC. In the J band, the nebula is brighter than the IRC itself, and the ratio of their peak intensities is 1.3. A small gap is seen in the J and H bands between the IRC and

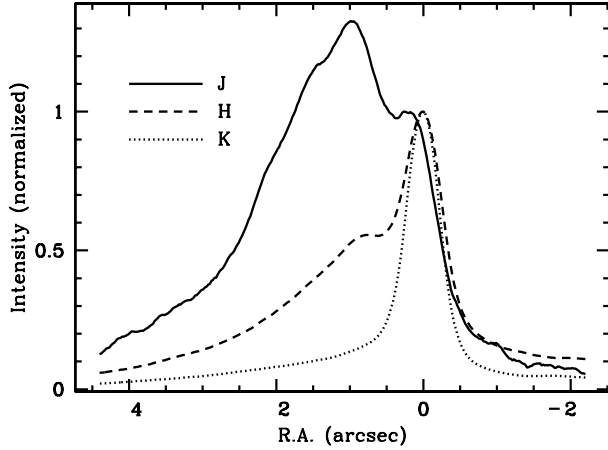


Fig. 2. E–W line profile through the IRC and its nebula. The intensity is averaged over $0''.4$ in N–S centered on the IRC. The intensity is normalized by the peak intensity of the IRC. The results are smoothed over $0''.4$ in R.A.

its nebula. It is difficult to consider this gap to be caused by the optically-thick disk, because the disk should hide the west side of the IRC that is the opposite side where the gap is seen. The gap may be due to a clumpy dust distribution.

3.1.2. Nature of the IRC

The magnitudes of the IRC estimated from small-aperture photometry are 16.2, 14.1, and 11.4 mag for the *J*, *H*, and *K* bands, respectively. The uncertainties are 0.1 mag for the *J* and *H* bands and 0.05 mag for the *K* band. The aperture radius was $0''.43$, $0''.54$, and $0''.65$ for the *J*, *H*, and *K* bands, respectively. These radii were selected so as to minimize the contribution of the nebulae. The measured magnitudes are fainter than previously determined (Li et al. 1994; Corcoran et al. 1995), probably because the extended nebulae contributed to the photometry in their larger apertures. The near-infrared colors of the IRC are $J - H = 2.2 \pm 0.3$ and $H - K = 2.5 \pm 0.2$, transformed from the CIAO system to the CIT system using equations described in Itoh et al. (2001). The colors of the primary are $J - H = 1.7$ and $H - K = 1.8$ (Li et al. 1994), and these values are typical of Herbig Ae/Be stars. In contrast, the IRC is redder than the primary. The near-infrared colors suggest that the IRC is a class I-like object (e.g., Itoh et al. 1996). In addition, the spectral index $\alpha \equiv d \log(\lambda F_\lambda) / d \log(\lambda)$ between $\lambda = 2.2$ and $10.8 \mu\text{m}$ (Lagage et al. 1993) is 3.1, which satisfies the definition of class I sources (Lada 1987).

In order to investigate the nature of the resolved companion further, we estimated the luminosities of the primary and IRC. We adopted the measurements of this work and Li et al. (1994) for the flux densities in near-infrared, Lagage et al. (1993) in $8\text{--}12 \mu\text{m}$ region, ISO photometry by Ábrahám et al. (2000) in $13\text{--}200 \mu\text{m}$, and the measurements of Sandell and Weintraub (1994) in the submillimeter. At wavelengths longer than mid-infrared, there are no measurements that resolve the primary and IRC. Therefore, we assume that the SED of the primary is the same as that of PV Cep. PV Cep is classified as group II Herbig Ae/Be similar to LkH α 198 based on the criteria of Hillenbrand et al. (1992), and is not known to have any close

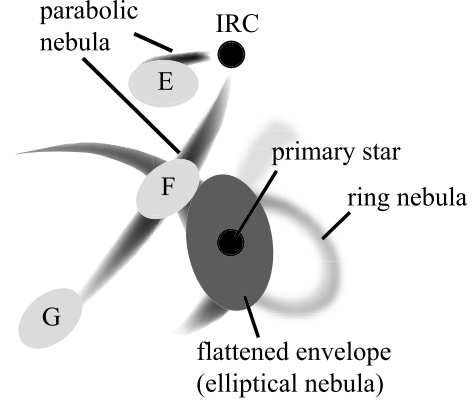


Fig. 3. Schematic description of the LkH α 198 binary system in the same region of figure 1. The gray regions labeled “E, F, G” denote the features in visible light described by Asselin et al. (1996).

companion. The classification of LkH α 198 is not affected by the IRC (Li et al. 1994). Furthermore, at $60\text{--}200 \mu\text{m}$, the adopted values contain the flux of a millimeter source located at $19''$ from the LkH α 198 primary. In order to remove the flux of the millimeter source, we calculated its contribution using the predicted blackbody fit by Sandell and Weintraub (1994). At submillimeter wavelengths, measurements were also contaminated by the millimeter source, although photometry was carried out with an aperture $< 19''$. We assume that the submillimeter flux comes from the primary and IRC because it is difficult to estimate the contribution from the millimeter source. This assumption is not crucial to our conclusions because the luminosity at $200\text{--}1000 \mu\text{m}$ is below 2% of the total luminosity at $1\text{--}1000 \mu\text{m}$. The calculated luminosities at $1\text{--}1000 \mu\text{m}$ are $\sim 140 L_\odot$ for the primary, and $\sim 60 L_\odot$ for the IRC.

The situation that the IRC has extremely red near-infrared colors and slightly lower luminosity suggests that its mass is lower and its age is younger than the primary. Another possible explanation is that the red colors of the IRC are due to its nearly edge-on disk geometry, regardless of its actual age (e.g., Masunaga, Inutsuka 2000).

3.2. Nebulae of the Primary

The high-resolution observations reveal nebulae associated with the primary. We show a schematic diagram of the surroundings of LkH α 198 in figure 3. The ring nebula in the west and the reflection nebula elongated to the east (figure 4) suggest the outflow activity of the primary.

In the vicinity of the primary star, an elliptical nebula which elongates in the northeast–southwest direction is detected. The nebula corresponds to the “infrared bar” described by Koresko et al. (1997) in the *H*-band speckle imaging, extending $2''\text{--}3''$ from the star in both directions along P.A. = $20^\circ\text{--}30^\circ$. We fitted an ellipse to the nebula in the *H* band by a least-squares regression routine, giving a resultant P.A. = 15° measured from the north-east direction at a semimajor axis of $2''$. This P.A. is perpendicular to the *H*-band polarization angle of 96° in the $\sim 1''$ dust component around the LkH α 198 primary (Leinert et al. 1991). This suggests that the elliptical nebula is a reflection nebula illuminated by LkH α 198 itself.

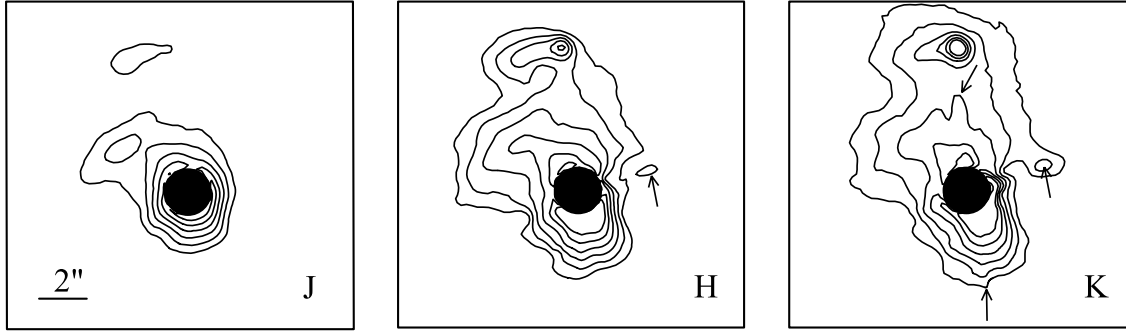


Fig. 5. *JHK*-band contour map after subtracting the PSF from the primary star. The contours are logarithmic starting from the highest level of 76, 53, and 70 mJy arcsec⁻² at *J*, *H*, and *K*, respectively, and spaced with a factor of $10^{-0.2}$ between successive levels. The occulting mask used is $1''.5$ in diameter, but the unusable region after subtraction in the figure is $2''$. Note that the emission indicated by arrows are due to spider spikes.

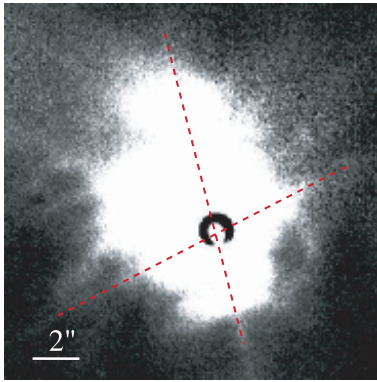


Fig. 4. *H*-band image to show the faint nebulosity around LkHα 198. The PSF is not subtracted. The red dashed lines indicate the direction of the secondary spider structure. Several faint nebulae are observed, including the western ring nebula and the eastern reflection nebula associated with the primary. Also see figure 3. North is up, and east is to the left.

In spite of using a coronagraph, the stellar flux is still dominant near the masked central bright star. In order to retrieve the nebula shape in the close vicinity of the primary star, we subtracted the coronagraphic PSF image constructed from observations of HD 224784. Figure 5 shows the resulting contour map after approximate centering and scaling. The resultant structure is more bar-like at the longer wavelengths. It suggests that the dust density is higher along the axis of P.A. = 15° , which is nearly perpendicular to the direction of the reflection nebulae.

We examined the radial profile of the southern part of the nebula in the *H* and *K* bands after subtracting the PSF along the axis of P.A. = 15° . The profile can be measured beyond the obscuration from the coronagraphic mask at a distance from the star of $r \geq 550$ AU. The surface brightness is proportional to $r^{-2.3}$ at $r \leq 1200$ AU and $r^{-3.9}$ at $r \geq 1200$ AU in *H* band. The same behavior is seen also in *K* band, that $r^{-2.1}$ at $r \leq 1200$ AU and $r^{-3.3}$ at $r \geq 1200$ AU. The radial profile indicates that the dust distribution changes at $r \sim 1200$ AU. This size of $r \sim 1200$ AU is consistent with the typical size of the envelope around T Tauri stars, suggesting that the denser central region of the nebula ($550 \leq r \leq 1200$ AU) corresponds to the flattened “envelope” structure, rather than the accretion disk.

Our image shows large-scale (~ 1200 AU) envelope whose elongation is perpendicular to the axis of the reflection nebulae (the ring nebula in the west and the reflection nebula in the east). However, for the inner part, the polarization position angle was measured to be 154° in the *H* band (Leinert et al. 1991) and 138° in the optical band (Piirola et al. 1992). In addition, the optical jet (HH 164; Corcoran et al. 1995), which has P.A. = 160° , is thought to be associated with the primary. These results suggest that the primary has a small-scale (< 120 AU; Piirola et al. 1992) disk with P.A. of the disk plane being 50° – 70° . A misalignment of the inner disk and the outer circumstellar matter has been found for other young stellar objects, such as R CrA (Ward-Thompson et al. 1985). Although there is some debate on the true exciting sources, Ward-Thompson et al. (1985) suggest that the jet is collimated by an inner disk, the large-scale outflow is collimated by an outer disk (corresponding to our envelope), and two disks could be tilted toward each other. A similar structure has been proposed for Chamaeleon infrared nebula (Gledhill et al. 1996). Much higher resolution observations are necessary to resolve the inner disk and to establish a relation between the inner and outer disks.

The elongated envelope is also highly asymmetric in P.A. = 15° ; the southern part is much brighter than the northern one. Such asymmetry might be due to the existence of a companion, either the IRC or a still unresolved source.

4. Summary

As a part of the high-resolution coronagraphic survey of Herbig Ae/Be stars, we carried out *JHK* imaging of LkHα 198. The obtained images resolve the IRC and reflection nebulae associated with each of the primary and IRC. The main results can be summarized as follows:

1. The near-infrared colors of the IRC suggest that it is a class I-like object.
2. The IRC is associated with a parabolic reflection nebula, indicating that it is an outflow source.
3. The IRC is most likely the driving source of HH 161 rather than the primary or millimeter source.
4. The primary is associated with complex reflection nebulae. One is a large ($\gtrsim 3000$ AU) nebula probably associated with the outflow activity of the primary, while

the other is a small ($r \sim 1200$ AU) asymmetric flattened envelope.

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