UNVEILING SU AURIGAE IN THE NEAR-INFRARED: NEW HIGH SPATIAL RESOLUTION RESULTS USING ADAPTIVE OPTICS

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ABSTRACT

We present new results on the circumstellar nebulosity around SU Aurigae, a T Tauri star of about 2 $M_\odot$ and 5 Myr old at 152 pc in the J, H, and K bands using high-resolution adaptive optics imaging (0\arcsec\,30) with the Penn State Near-IR Imager and Spectrograph at the 100 inch (2.5 m) Mount Wilson telescope. A comparison with Hubble Space Telescope STIS optical (0.2–1.1 $\mu$m) images shows that the orientation of the circumstellar nebulosity in the near-IR extends from position angle 210\arcdeg to 270\arcdeg in the H and K bands and up to 300\arcdeg in the J band. We call the circumstellar nebulosity seen between 210\arcdeg and 270\arcdeg an “IR nebulosity.” We find that the IR nebulosity (which extends up to 3.5\arcsec in the J band and 2.5\arcsec in the K band) is due to scattered light from the central star. The IR nebulosity is either a cavity formed by the stellar outflows or part of the circumstellar disk. We present a schematic three-dimensional geometric model of the disk and jet of SU Aur based on STIS and our near-IR observations. According to this model, the IR nebulosity is part of the circumstellar disk seen at high inclination angles. The extension of the IR nebulosity is consistent with estimates of the disk diameter of 50–400 AU in radius, from earlier millimeter K-band interferometric observations and SED fittings.

Key words: scattering — stars: formation — stars: individual (SU Aurigae) — stars: pre–main-sequence — techniques: high angular resolution — techniques: image processing

1. INTRODUCTION

SU Aurigae is a T Tauri star located in the Taurus-Auriga complex of dark molecular clouds at a distance of 152 pc (DeWarf et al. 2003; Hipparcos Catalogue). Its spectral type is G2 III, mass is $\sim 2 M_\odot$, and age is about 4–5 Myr (DeWarf et al. 1998, 2003). Recent observations by Nadalin et al. (2000) have shown short time variability in the B-band magnitude that they attribute to protoplanetary materials orbiting in the circumstellar disk. Petrov et al. (1996) have found the existence of a gas outflow from the star using their spectroscopic results.

The Hubble Space Telescope (HST) STIS coronagraphic observations by Grady et al. (2001) from 0.2 to 1.0 $\mu$m have revealed fanlike structures extending up to a distance of 12\arcsec–15\arcsec in the west to southwest direction. These, according to the authors, are mainly reflection nebulae scattering the light of the central star. They also detected streaming filamentary structures going radially outward from the star, which could be due to gas outflow either from the star or from the parent molecular cloud.

Our motivation comes from the STIS images of SU Aur and from the fact that no report of high spatial resolution near-infrared images of the star could be found in the literature to this date. Therefore, we observed the source in the near-infrared (J-, H-, and K-band images) using adaptive optics and applied the technique of point-spread function (PSF) subtraction to investigate the circumstellar region of SU Aur with high spatial resolution (0\arcsec\,25–0\arcsec\,30). In this paper we present the results of our investigation (of SU Aur). In § 2 we describe observations and data analysis procedure, § 3 introduces the results, in § 4 we discuss our results, and we present our conclusions in § 5.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observations

SU Aurigae was observed in the J, H, and K photometric bands during 2002 October at the 100 inch (2.5 m) telescope of Mount Wilson using its natural-star adaptive optics (AO) system (Shelton et al. 1995) and the Penn State Near-IR Imager and Spectrograph (PIRIS; Ge et al. 2003). The detector is a 256 $\times$ 256 PICNIC array with 40 $\mu$m pixels. The plate scale is 0.082 pixel$^{-1}$, providing a field of view of 21$''$. PIRIS is also equipped with cold pupil masks in the pupil plane to reduce the thermal background (particularly in the K band).

The night of observations (2002 October 19) was photometric with subarcsecond seeing, and the FWHM of the star’s PSF after the AO correction was measured to be 0\arcsec\,25. Seven images of SU Aur with 60 s exposures in each photometric band were recorded when the object was near zenith (air mass close to 1.00). Two PSF stars were also observed, namely, BD +40\arcdeg\,248 (spectral type G2 V, PSF1) and Gl 46.1 (spectral type G5 V, PSF2). Gl 46.1 was observed 3.5 hr before the SU Aur observations as part of a different program (Shelton et al. 1995). We found the existence of a gas outflow from the star using their spectroscopic results. The night of observations (2002 October 19) was photometric with subarcsecond seeing, and the FWHM of the star’s PSF after the AO correction was measured to be 0\arcsec\,25. Seven images of SU Aur with 60 s exposures in each photometric band were recorded when the object was near zenith (air mass close to 1.00). Two PSF stars were also observed, namely, BD +40\arcdeg\,248 (spectral type G2 V, PSF1) and Gl 46.1 (spectral type G5 V, PSF2). Gl 46.1 was observed 3.5 hr before the SU Aur observations as part of a different program (Shelton et al. 1995). We found the existence of a gas outflow from the star using their spectroscopic results.

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same instrument, and its PSF has an FWHM of \(0^{\prime}28\) and has a similar shape.

The PSF stars were selected based on the similarity of their brightness and spectral type to SU Aurigae. For instance, the \(J\), \(H\), and \(K\) magnitudes of BD +40°248 are 5.76, 5.35, and 5.27, while those of Gl 46.1 are 5.50, 4.96, and 4.75, respectively (from 2MASS All Sky Point Source Catalog). From the same catalog the SU Aur \(J\), \(H\), and \(K\) magnitudes are 7.20, 6.56, and 5.99, respectively. Three exposures of 1, 10, 20, and 30 s in each photometric bands (\(J\), \(H\), and \(K\)) of the PSF stars were taken. This procedure facilitates the scaling of the PSF stars with respect to the PSF of SU Aur. Six sky images were also taken before and after the observations of all the sources. These sky frames were combined to obtain sky frames for sky subtraction. Normalized twilight sky images were used as flat frames in the \(J\), \(H\), and \(K\) bands.

2.2. Data Analysis and the Procedure of Scaled PSF Subtraction

Data analysis was performed using various IRAF tasks. All images went through a standard pipeline of sky subtraction and flat-field correction before the specialized tasks of PSF matching and subtraction. Figure 1 shows the \(J\)-band image of SU Aur before the PSF subtraction and a scaled and azimuthally smoothed (in sectors of \(15^{\prime}\)) mean image of the PSF star. Figure 2 shows a radial plot (azimuthally averaged over \(360^{\circ}\)) of the mean PSF star in Figure 1.

Since SU Aur is known to possess a large extended nebulosity (Grady et al. 2001; Woodgate et al. 2003; Nakajima & Golimowski 1995), the PSF matching of SU Aur with that of the PSF stars is not a straightforward task. The usual procedure of matching the wings of the PSF of the object (SU Aur) with that of the PSF stars was not possible because of the presence of extended emission from SU Aur. Therefore, an alternate procedure was adopted: (1) To get rid of the high-frequency noise and to generate a symmetric smooth PSF function, each PSF image was azimuthally averaged over sectors of \(15^{\prime}\). (2) A comparison of the relative brightness of SU Aur with that of the PSF stars using their apparent magnitudes in the respective bands was made. (3) The intensity of the PSF star images were scaled to SU Aur. For instance, BD +40°248 (PSF1) is 1.2 mag or 3 times brighter than SU Aur in the \(H\) band, so that the intensity from a 20 s exposure frame of PSF1 should match that of 60 s exposure of SU Aur.

The third step was repeated for all exposure times of the PSF stars by multiplying by suitable factors. Thus, the brightness of both the PSF stars (PSF1 and PSF2) were scaled to that of SU Aur and were cross checked by subtracting one scaled PSF star from the other until minimal intensity residuals were found in the scaled PSF1 – PSF2 images. The residual patterns of PSF1 – PSF2 subtraction are shown in Figure 3. Because of the difference in spectral type of stars (in the present case PSF1 is G2 and PSF2 is G5) the difference in slope of the continuum across the filter bandwidth leaves a diffraction pattern as a residual. For example, the work of Krist et al. (1998) on PSF subtraction of one normal star from the other using the HST data has clearly demonstrated these effects.

At the end of the third step we obtained two scaled PSF star images that are similar. The final PSF star image was

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**Fig. 1.** — (a) \(J\)-band image of SU Aur before the PSF subtraction. (b) Scaled and azimuthally smoothed (in sectors of \(15^{\prime}\)) mean PSF star image in the \(J\) band. North is up, and east is to the left.

**Fig. 2.** — Radial plot (azimuthally averaged over \(360^{\circ}\)) of the mean PSF star in Fig. 1 showing the contrast levels in log scale vs. radial distance in arc-seconds.
constructed by taking the mean of the two scaled PSF star images. We note here that the x-y positions of the PSF image were matched with that of SU Aur up to one-fifth of a pixel for good subtraction. Figure 4 shows PSF-subtracted images of SU Aur using the same contrast level as that of Figure 3. The HST STIS data (0.2 to 1.1 μm; Grady et al. 2001) in Figure 4 was downloaded from the HST archive, analyzed by the standard STSDAS-IRAF pipeline routines and then over-plotted with the contour levels of the J-band intensity levels from 15.0 to 9.0 mag at an interval of 0.5 mag. We note that we did not perform PSF subtraction on the STIS image since the STIS image is only used for comparison of brighter regions between the optical and near-infrared nebulosity.

Figure 5 shows the mean surface brightness of the disk with respect to the distance from the star in the J, H, and K bands. The mean surface brightness was calculated by summing up the disk brightness in the azimuthal direction between position angles (P.A.s) 210° and 310° and dividing it by the total number of spatial resolution elements (in this case 0.3 × 0.3, 4 × 4 pixel elements). It is clear that the procedure of PSF subtracting images taken with the Mount Wilson AO system can be used to detect faint extended emission up to contrast levels of 10⁻⁴ per resolution element (which is 0.3 × 0.3) beyond 1″ from the central bright star. The crosses with error bars show the residuals of PSF1 – PSF2. The accuracy of the photometry is measured to be 0.2 mag. The lines in the J, H, and K bands therefore show instrument detection limits. In the present work we consider only the extended structures of SU Aur that are beyond 1″.

3. RESULTS

As is evident from Figures 4 and 5, the brightness varies between 12 and 15 mag per resolution element. The brightness of the circumstellar nebulosity scales with the distance from the star as 1/√r 1.2 to 1/√r 2 between 1″ and 4″ (where r is the distance from the star in arcseconds) and maximum extent up to 2.5″ in the J band and less than 2.5″ in the K band. The size of the circumstellar nebulosity remains intermediate in the H band. In the J band, the nebulosity is prominent from P.A. = 210° to 300° and faintly visible from P.A. = 50° to 115°.

The geometry of the extended nebulosity is more intriguing when compared with the STIS image (Fig. 4). Although the overlapping contours of the J-band image intensity show regions bright in the STIS image, it also shows a region that is between P.A.s 200° and 250°. In the H and K bands only the latter region is seen clearly and will be referred to as the “IR nebulosity.”

Grady et al. (2001) attributed the radially streaming filamentary structure (seen in the STIS image) at P.A. = 295°–300° as the blue jet emerging from the star. It is worth mentioning here that ground-based coronagraphic images in the R and I bands using adaptive optics also show similar features (Nakajima & Golimowski 1995). These coronagraph images show both the radially outward streaming nebulosity seen in the STIS image and the region between P.A.s 200° and 250° in our near-IR images. Their work shows brightness of about 17 and 16.5 mag arcsec⁻² in R and I bands, respectively, at a distance
of $3''-4''$ from the star between P.A.s 200° and 250° and about 14.5 mag arcsec$^{-2}$ (in $R$ and $I$) between P.A.s 260° and 300°.

4. DISCUSSION

SU Aur is known to possess a large accretion disk of up to 400 AU and an outer envelope (Akeson et al. 2002, hereafter ACBC; Oliveira et al. 2000). Both ground-based and HST STIS coronographic images of SU Aur (Nakajima & Golimowski 1995; Grady et al. 2001) in the optical wavelengths have shown spatially resolved outflows and a reflection nebula mainly due to scattered star light. In the near-IR, however, the PSF-subtracted $J$, $H$, and $K$ images of SU Aur (see Figs. 4 and 5) reveal an extended nebulosity at angles (P.A. = 210°–270°) where there is little optical emission (Fig. 4; see also Nakajima & Golimowski 1995). The region where the strongest optical nebulosity is seen is between P.A.s 295° and 310° (Grady et al. 2001). Therefore, the regions probed in the near-IR are different from those in the optical wavelengths. We discuss the IR nebulosity below.

There can be two explanations for the IR nebulosity: (1) the region of IR nebulosity is the opening of a cavity in the parent molecular cloud seen almost edge-on and formed by the stellar outflow (Stapelfeldt et al.1998), or (2) it is part of the circumstellar disk itself seen at high inclination angles ($\geq$65°). In either case the region may suffer greater extinction in the optical wavelengths (see Cotera et al. 2001). We present the likelihood of both scenarios below, with emphasis on the second one (that the IR nebulosity is part of the disk seen in the scattered light of the central star). We also present a geometrical model based on the disk assumption.
The IR nebulosity can be a cavity formed by the bipolar outflows from the star (Stapelfeldt et al. 1998). Scattered light model calculations on T Tau and IRAS 04016+2610 by Wood et al. (2001) have shown that cavities formed by multiple stellar outflows and misaligned circumstellar disks can be seen in the scattered light of the central star up to a radius of 500 AU. The observed IR nebulosity in SU Aur could be a cavity formed by the blue jet. However, a very large opening angle of greater than $70^\circ$ for the blue jet (Grady et al. 2001) would be necessary to explain the P.A. of the IR nebulosity.

The IR nebulosity could be the part of the circumstellar disk seen almost edge-on. The geometrical model describing the orientation of the disk with respect to the observer is described by ACBC. ACBC calculated the most probable physical parameters of the disk, such as the P.A., the angle of inclination, and the extent of the disk from $K$-band and millimeter interferometry and SED curve fittings. They found that the disk outer radius could be 50–400 AU ($0.3-2.6$) with an angle of inclination of about $62^\circ$ and a P.A. of $130^\circ$. ACBC state that their data set on SU Aur is not sufficient to constrain the model parameters, and the disk parameters quoted by ACBC are the most probable ones from the model fittings. However, according to STIS coronagraphic observations (Grady et al. 2001) the blue jet is at P.A. $= 295^\circ$ and a probable red jet is at P.A. $= 114^\circ$.

We propose a schematic three-dimensional geometric model for SU Aur based on our near-IR observations and the STIS observations (Grady et al. 2001). The model (not to scale) is shown in Figure 6. The disk is seen close to edge-on (angle of inclination $= 65^\circ$ or greater; Grady et al. 2001; ACBC) and at an azimuthal angle of about $180^\circ$ (see Fig. 6). Thus one side of the disk surface faces toward the observer along with one of the jets (the blue jet). The part of the disk surface facing toward the observer could be seen as the IR nebulosity; and the remaining part of the disk could be obscured as a consequence of high optical extinction (Cotera et al. 2001). According to these authors, scattered star light through the disk can suffer from very high extinction of $A_V = 80$ or more (also see Wood et al. 2001).

 Furthermore, if the IR nebulosity is part of the optically thick disk seen almost edge-on, then we can compare the total flux of the IR nebulosity with that of the model of ACBC. Such a comparison will also indicate if the IR nebulosity is due to scattered light from the star. Figure 7 of ACBC shows the flux (in janskys) of the theoretical model of the disk that was used to fit the SED. We estimate an upper limit for the total flux (in janskys) of the IR nebulosity in each band, assuming an area covered by an annular ring of radii $1''$ and $2.6''$ and compared these values with the model of ACBC. These are listed below as (values from present work)/(model values of ACBC) in $J$, $H$, and $K$ respectively: $(0.8)/(0.10)$, $(0.2)/(0.5)$, and $(0.11)/(1.1)$.

If the model values are reliable, then it is possible that in the $J$ band the observed flux of the IR nebulosity is dominated by the star-scattered light from the disk and the stellar jet (as in the optical wavelengths of the STIS image) rather than the disk flux itself. The comparison between the $H$-band fluxes are the closest, which may be a coincidence. It is most likely that the total flux in the $H$ band is dominated by the dust scattering. In the $K$ band we find that the observed disk flux and the model values differ by an order of a magnitude. The scattering in the $K$ band is less compared with the $J$ band and optical wavelengths and is expected to be dominated by the disk’s thermal emission. ACBC predicts the disk temperature to be 55–150 K at 10 AU and is expected to fall at larger radii. Since the present work is sensitive only to distances greater than $1''$ (160 AU), we are unable to see the thermal component from the disk and have measured only the scattering component.

5. CONCLUSIONS

We present PSF-subtracted high spatial resolution images ($0'.30$) of the circumstellar region of SU Aurigae (between $1''$
and 4") in the J, H, and K bands. These images show a distinct region that is bright in the near-IR, which we call the IR nebulosity. The IR nebulosity is prominent between position angles 210° and 270° and extends up to 3°5 in the J band and 2°5 in the K band. We present two scenarios about the nature of the IR nebulosity: (1) it could be a cavity formed by the stellar outflows, or (2) it is part of the circumstellar disk observed at high inclination angles (≥65°). We favor the latter case and we present a schematic three-dimensional geometric model describing the orientation of the disk and jet of SU Aur with respect to the observer. However, more observations are necessary with a large telescope equipped with AO and perhaps with coronagraphs and polarimetry to resolve spatial structures close to the star (down to 0.1") for detailed modeling.

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