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Mid-infrared imaging of a young bipolar nebula in the S287 molecular cloud⋆

M. E. van den Ancker

European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany
e-mail: mvanden@eso.org

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ABSTRACT

We present diffraction-limited images in the 11.3 μm PAH band and in the continuum at 11.9 μm of the S287B star forming region obtained with the newly commissioned mid-infrared imager/spectrometer VISIR at the VLT. In both filters five point-like sources are detected, of which at least one has a spectral energy distribution reminiscent of a Lada Class I source. We also report on the discovery of a new Herbig Ae star in this region. It is particularly striking that the brightest mid-infrared source in this region has not been detected at shorter wavelengths; it is a good candidate to be the driving source of the bipolar molecular outflow and optical reflection nebulosity previously reported in S287B.

Key words. circumstellar matter – stars: formation – ISM: S287B – reflection nebulae – infrared: stars

1. Introduction

The formation of massive stars is currently one of the most hotly debated topics in astrophysics. Massive stars reach the Zero-Age Main Sequence (ZAMS) while still deeply embedded in their infalling envelope. One would expect the strong radiation pressure from the newly formed star to clear its natal envelope when the star has reached a mass of $\sim$10 $M_\odot$, halting the further build-up of mass (e.g. Stahler et al. 2000). Yet we observe stars that are apparently more massive than this limit. Two mechanisms have been proposed to circumvent this dilemma and allow the creation of stars more massive than 10 solar masses: mass build-up through disk accretion, and mergers of two or more less massive stars in dense stellar clusters. It is currently not clear which of these two mechanism is responsible for forming massive stars within our galaxy (e.g. Bonnell & Bate 2002; Yorke & Sonnhalter 2002; Bally & Zinnecker 2005).

To tackle this problem observationally, one would like to study the earliest stages of the formation of a massive star. Since these stars are still heavily obscured by their infalling envelope (A_V ranging from 20 to >1000), the mid-infrared is the most natural wavelength regime for this type of study. Of particular interest may be the small group of Young Bipolar Nebulae, in which the strong outflow from the embedded source has created a bipolar cavity, allowing some of the UV-visual radiation from the central star to escape the system (see e.g. Staude & Elsässer (1994) for a comprehensive review). Young Bipolar Nebulae have been relatively well studied at optical to near-infrared wavelengths. However, these wavelengths are dominated by scattered light from the nebula, offering little information about the processes occurring in the innermost parts. In contrast, the mid-infrared continuum is able to probe regions close to the central object, and reveal the true location of the illuminating source. Moreover mid-infrared emission is able to penetrate large sections of the bipolar nebula, tracing the inner surface of the biconical cavity created by the central source.

In this Letter we aim to contribute to the problem of the formation of massive stars by focussing on a little-studied bipolar nebula located in the molecular cloud associated with the H II region S287. The S287 molecular cloud (l = 218.10°, b = −0.37°, d = 2.3 kpc; Williams & Maddalena 1996) is an elongated structure, extending over about 1.5° parallel to the galactic equator. It consists of two main components of similar sizes and CO column densities, which are connected by a tenuous bridge. The northern component harbours its densest core, associated with the bipolar nebula NS14. The faint H II region S287 is associated with the other component. S287 is a likely location of on-going star formation. The S287 cloud and another nearby cloud mapped by Maddalena & Thadeus (1985) may all have been part of a larger molecular cloud complex that included G216−2.5 that has been partially dissociated by the S287 OB stars.

The intermediate-luminosity IRAS source IRAS 06571−0441 is located in the vicinity of a small reflection nebulosity at the northern border of S287. The region is associated with a bipolar outflow mapped in CO and traced by a

⋆ Based on observations collected at the European Southern Observatory, Chile (program ID 60.A-9269(A)).

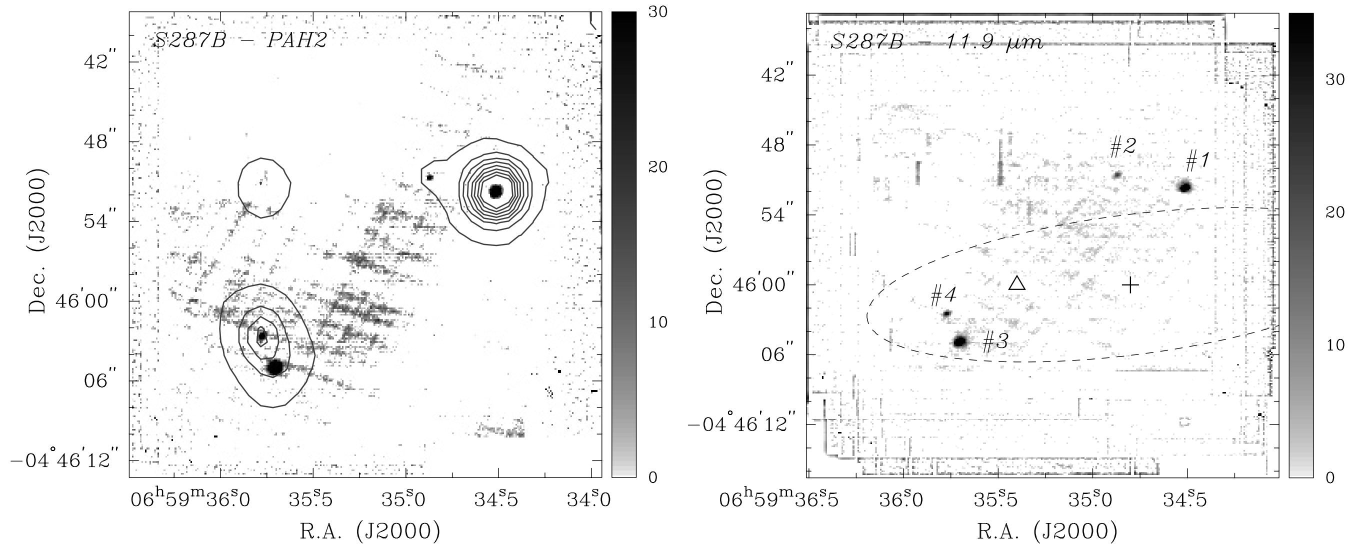

Fig. 1. Greyscale images of the S287B region in the PAH2 (11.3 μm; *left*) and 11.9 μm continuum (*right*) filters. The overlay in the PAH2 image show contours of the K_s (2.2 μm) image from the 2MASS survey. In the 11.9 μm continuum image we also show the IRAS position (cross) and error ellipse (dashed curve) of IRAS 06571−0441. The position of MSX G218.1025−00.3638 is marked with a triangle. Sources #1–#4 are also labelled in this image. Source #5 is located south of the area shown here; it is only detected in the chopped (negative) beam. The low-level diagonal "striping" pattern seen in the background of both images is an artifact caused by imperfections in the subtraction of thermal emission from the sky and the telescope support structure.

string of Herbig-Haro objects (Neckel & Staude 1992). The IRAS source is located in the vicinity of a likely young bipolar nebula. Deep optical images by Neckel & Staude (1992) reveal two regions of reflection nebulosity separated by a dark lane ($A_V > 20$ mag). Its bolometric luminosity of $\approx 440\ L_\odot$ suggests the embedded source to be a massive (possibly Herbig Be) YSO. Although no definite optical counterpart was detected, Neckel & Staude (1992) found that a substantial fraction of the optical light scattered by the reflection nebulosities consists of broad Hα emission with pronounced P-Cygni profiles, in line with the emission originating in a Herbig Ae/Be or T Tauri wind.

In this Letter we present high-spatial resolution mid-infrared images of the vicinity of the bipolar nebula associated with IRAS 06571−0441. We report the detection of a likely counterpart for the embedded source, as well as several less luminous mid-infrared sources. We conclude that the S287B region is a likely site of still on-going massive star formation.

2. Observations

Mid-infrared images of S287B in the PAH2 (λ_c = 11.26 μm, $\Delta\lambda$ = 0.59 μm) filter and in the continuum filter centered at 11.88 μm (PAH2_2, $\Delta\lambda$ = 0.37 μm) were taken on November 27, 2004 as part of Science Verification of the newly installed *VLT Imager and Spectrometer for mid Infrared*[1] (VISIR) at the *Very Large Telescope* (VLT). VISIR uses a DRS (former Boeing) 256×256 BIB detector. The pixel scale was set to 0.″127, resulting in a 32.5″ × 32.5″ field of view. Subtraction of the thermal emission from the sky, as well as the telescope itself, was achieved by chopping in the North-South direction with a chop throw of 20″, and nodding the telescope in the opposite direction with equal amplitude. The cosmetic quality of the images was further improved by superimposing a random jitter pattern (with maximum throw 2″) on the nodding sequence, so as to minimize the effect of bad pixels in the detector array on the final science data. Total integration times were 15 and 30 min for the PAH2 and the 11.9 μm continuum filter, respectively.

[1] http://www.eso.org/instruments/visir/

The mid-infrared standard stars HD 22663 (K1 III) and HD 59311 (K5 III), observed just before and after the science observation, were used to flux calibrate the data and as point spread function (PSF) reference stars. The flux calibration obtained by using one or the other of these two standard stars differs by about 2%. For our final calibration we have adopted an average of both calibrations, and we adopt a 2% systematic error on the absolute flux calibration based on this difference. Although the seeing at the time of observation was 0.″9 in the optical, the FWHM of our standard star images is only 0.35″, comparable to the diffraction limit of the VLT at 11.3 μm (0.28″).

After a standard data reduction consisting of co-adding of frames, flat fielding and bad pixel removal, the chopped and nodded images of S287B were combined into one single frame per filter, shown in Fig. 1. In both filters, we detect five point-like sources. In the remainder of this paper we will refer to these sources as #1 to #5, in order of increasing right ascension. Note that source #5 was only detected in the chopped (negative) beam; it is located South of the area shown in Fig. 1. All five detected sources appear point-like. By comparison with our PSF reference stars, we derive upper limits of <0.″15 on the spatial extent of these compact sources. No evidence for extended emission could be detected in any of our mid-infrared images. Synthetic aperture photometry was performed on all five point sources using a circular aperture of 15 pixels (2.″0)

Table 1. Detected sources in S287B.

No.	RA (J2000)	Dec (J2000)	$S_{\rm PAH2}$ [mJy]	$S_{11.9\,\mu{\rm m}}$ [mJy]	2MASS ID
# 1	06:59:34.52	−04:45:51.8	418 ± 12	376 ± 21	06593451−0445517
# 2	06:59:34.87	−04:45:50.7	19 ± 4	37 ± 4	06593481−0445506
# 3	06:59:35.71	−04:46:05.0	465 ± 9	443 ± 9	
# 4	06:59:35.77	−04:46:02.6	52 ± 2	68 ± 5	06593576−0446025
# 5	06:59:35.99	−04:46:15.2	22 ± 12	37 ± 5	

diameter, with a 5 pixel wide annulus surrounding this aperture used to subtract any background residuals. Different choices of the radii did not significantly alter our results. The resulting new mid-infrared photometry of the five detected sources in S287B is listed in Table 1. Listed errors include contributions due to photon noise, residuals from the background subtraction, and pixel gain variations (which are strongly reduced due to our choice of an observing strategy including dithering), as well as the 2% error in the absolute flux calibration.

Although the relative astrometry of the VISIR data is highly accurate, the absolute positions derived from the data is subject to an uncertainty – mainly due to the finite accuracy of the telescope pointing – of a few arcseconds. A careful inspection of our images shows that sources #1, #2 and #4 can be associated with a counterpart that has been detected in the $K_{\rm s}$ (2.17 μm) band by the 2MASS survey (Fig. 1). We have therefore registered our images using the 2MASS coordinates of source #1 (2MASS 06593451−0445517). Subsequently, the positions of all five detected point sources were determined by the fitting of a Gaussian to each source. In Table 1 we also report the so derived position for each source. We estimate this astrometry to be accurate at the 0.″1 level.

3. Analysis and discussion

An inspection of images from the *Digitized Sky Survey*[2] (DSS) reveals likely optical counterparts for our sources #1 and #4. Based on these identifications, we have constructed optical-infrared Spectral Energy Distributions (SEDs) of the five sources detected in our VISIR data (Fig. 2). Upper limits to the near-IR and optical fluxes were derived from the 2MASS and DSS data and are plotted here as well.

Our source #1 – identical to star 1 in the field of IRAS 06571−0441 in the nomenclature of Neckel & Staude (1992) – is surrounded by a small reflection nebula in the DSS images. No trace of this nebulosity was recovered at the mid-infrared wavelengths samples by our VISIR data. Source #2 may be identified with the faint feature b in the field of IRAS 06571−0441 detected by Neckel & Staude (1992). Sources #3 and #4 are located close to the nebulous knot of material (f in the terminology of Neckel & Staude) they identified as a Herbig-Haro object.

The relative faintness of source #2 in our mid-infrared images clearly shows that it is not the optical counterpart of IRAS 06571−0441, as suggested by Neckel & Staude. The *IRAS Point Source Catalogue* (v. 2) positional error ellipse of

[2] `http://www-gss.stsci.edu/Dss/dss_home.htm`

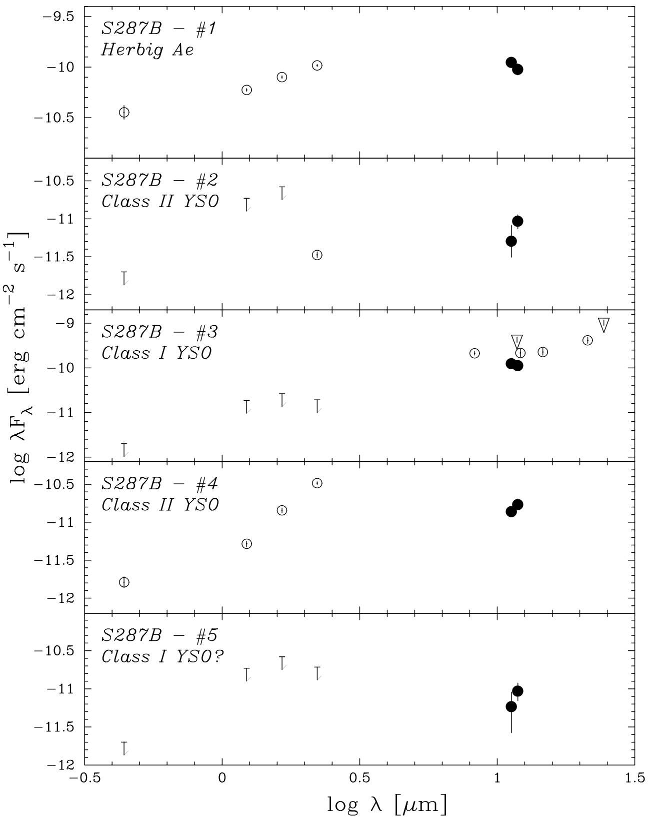

Fig. 2. Spectral Energy Distributions (SEDs) of all five detected sources in the S287B region. Open circles show data from the GSC2.2, 2MASS and MSX catalogues. The new VISIR photometry is shown as filled circles. IRAS data are indicated by triangles.

IRAS 06571−0441 is instead compatible with our source #3 or source #4 (Fig. 1). Based on its brightness in the VISIR images, and the lack of an associated 2MASS source – indicative of a very red energy distribution – we identify our source #3 as the likely counterpart of IRAS 06571−0441. We note, however, that its 11.9 μm flux in our VISIR images is significantly lower than the IRAS 12 μm flux; likely also extended mid-infrared below our detection limit is present. Curiously, the position of the counterpart of IRAS 06571−0441 detected by the *Midcourse Space Experiment* (MSX; Egan et al. 2003) does not correspond to any of the sources in our VISIR image; the presence of extended mid-infrared emission not detected in our images could possibly also explain this discrepancy.

Optical spectroscopy by Neckel & Staude (1992) has shown that star #1 is an early A-type star showing strong Hα emission. After correcting our photometry for foreground extinction adopting $A_V = 3.4$ mag (Neckel & Staude 1992), and the normal (i.e. $R_V = A_V/E(B-V) = 3.1$) interstellar extinction law by Cardelli et al. (1989), we derive the bolometric luminosity of star #1 to be around $L = 55\ L_{\odot}$, or about 20 times less luminous than the IRAS source. Our new mid-IR photometry reveals a strong mid-IR excess above levels that can be explained by the stellar photosphere in source #1 (Fig. 2). We conclude that this object is a likely new Herbig Ae star. The possible presence of intrinsic PAH emission at 11.3 μm from this object (Table 1) would suggest that it is a Meeus et al. (2001) group I source, i.e. it possesses a flared disk (Acke & van den Ancker 2004). Assuming an effective temperature of 8900 K (corresponding to a spectral type of A2; Schmidt-Kaler 1982), and the above-mentioned luminosity of 55 $L_{\odot}$, we derive a mass of 2.5−3.0 $M_{\odot}$ and an age of 2−5 Myr for this object by comparing its position in the Hertzsprung-Russell diagram with the pre-main sequence evolutionary tracks by Palla & Stahler (1993).

Although less information is available on source #2 and source #4, they also have energy distributions reminiscent of many class II YSOs. Their bolometric luminosities of 13 and 17 $L_{\odot}$, respectively, suggest that they may also be intermediate-mass young stars.

Source #3 and source #5 do not have a counterpart at wavelengths <10 μm. Source #3 (the likely counterpart of IRAS 06571−0441) is by far the most luminous object in the region ($L_{bol} \approx 1.3 \times 10^3\ L_{\odot}$). It is also very red: it has the energy distribution of a Lada Class I source. We conclude that source #3 appears to be a particularly good candidate for being the driving source for the bipolar outflow previously detected in molecular material. If the circumstellar material is distributed appropriately around the central star (e.g. in a disk seen close to edge-on), the star – although not visible in the optical from our vantage point – could also well be the dominant source illuminating the nebulosities in the field. The geometry of star #3 would be typical of that of a “bipolar nebula” with disk seen edge-on (cf. Staude & Elsässer 1993).

4. Conclusions

Our new VISIR observations have revealed five young stars in the part of S287 that was sampled by our data. In particular our mid-infrared data have revealed the driving source of the molecular outflow and the bipolar nebula seen in scattered light to be an embedded massive young star whose energy distribution is reminiscent of a Lada Class I source. We have also shown S287B to be associated with a likely new Herbig Ae star. The presence of presumably very young Class I objects in close vicinity to somewhat more evolved Class II objects is noteworthy. It certainly raises some questions about the scenario for star formation in this region: either not all sources are contemporaneous, or the class I (active accretion) phase must have lasted significantly longer in some objects in this regions than in others. Further research is necessary to clarify this issue.

It is also striking to note that the most luminous source in this region had not been detected at shorter wavelengths, nor had it been recognized previously from lower spatial resolution infrared data. This offers a candid illustration of the new insights that can be gained by the increase in spatial resolution in the mid-infrared that the combination of mid-infrared cameras on large-aperture ground-based telescope brings.

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