ABSTRACT

We present a mid-infrared (MIR) study of NGC 3576. The high-resolution images were taken at the Gemini South Observatory through narrow- and broadband filters centered between 7.9 and 18 μm. The nearly diffraction-limited images show IRS 1 resolved into four sources for the first time in the 10 μm band. The positions of the sources are coincident with massive young stellar objects (YSOs) detected previously in the near-infrared (NIR). The properties of each object, such as spectral energy distribution, silicate absorption feature, color temperature, and luminosities were obtained and are discussed. We also report observations of two other YSO candidates and the detection of a new diffuse MIR source without an NIR counterpart. We conclude that none of these sources contributes significantly to the ionization of the H II region. A possible location for the ionization source of NGC 3576 is suggested based on both radio and infrared data.

Key words: H II regions — infrared radiation — stars: early-type — stars: formation — stars: fundamental parameters

1. INTRODUCTION

Massive stars are responsible for many important phenomena in galaxies. They alter their environment through the emission of high-energy radiation and the deposition of momentum and mechanical energy into the interstellar medium through powerful winds. At the end of their lives, massive stars explode as supernovae, enriching the interstellar medium and causing shocks that may trigger the formation of new stars. The life and death of massive stars have a profound impact on both local and galactic scales.

Massive stars are believed to form in warm dense cores of molecular clouds. The earliest stage of a star in the process of formation is known as a prestellar core (PSC; Churchwell 2002). PSCs have not yet formed a central protostar and will not be detected in the near-infrared (NIR) or at radio wavelengths. Moreover, PSCs have temperatures of only 20 K and their spectral energy distributions (SEDs) peak in the far-infrared (FIR) at ~200 μm (Garay & Lizano 1999). The next phase of evolution toward the main sequence is known as the hot core (HC) phase. In this stage, a compact, dense, and warm molecular cloud core is believed to harbor a massive protostar in the process of rapid accretion, probably surrounded by an equatorial accretion disk (Kurtz et al. 2000). HCs are not detected at wavelengths shorter than ~10 μm, their SEDs are broader than a single temperature blackbody distribution, but they have a pronounced peak at ~100 μm. Since the protostar experiences a process of rapid massive accretion it cannot produce a detectable H II region (Osorio, Lizano, & D’Alessio 1999). After the accretion is over or greatly diminished, the Lyman continuum photons emitted by the massive star ionize the surrounding gas and an ultracompact H II (UC H II) region is formed. UC H II regions have SEDs also peaking at ~100 μm, but they can now be detected at shorter wavelengths, such as 1–2 μm (Wood & Churchwell 1989b; Hanson, Luhman, & Rieke 2000). The ionized gas is surrounded by a warm dust cocoon, which makes UC H II regions bright sources in the mid-infrared (MIR) as well. As the star evolves, the UC H II region expands and the natal gas and dust are swept away by intense stellar winds. Eventually, the ionizing star becomes visible, but it may have moved 10%–15% along its evolutionary track (i.e., after the zero-age main sequence) at this stage (Garmany 1994), and important questions regarding the formation of massive stars and their environment can no longer be addressed directly.

NGC 3576 harbors at least a dozen intriguing objects with color indexes H−K > 2, identified by Figuerêdo et al. (2002, hereafter FBDC). The K-band spectra of some of the brighter sources do not show any photospheric features. Moreover, the CO 2.3 μm band head is seen in emission or absorption in the spectra of four of these objects. Although the presence of this feature in emission or absorption has been explained by a variety of mechanisms, such as circumstellar disks, stellar or disk winds, magnetic accretion,
instabilities in the inner regions of accretion disks of low-mass stars, or free-falling gas along field lines (see the references in FBDC), disk emission is the most preferred model, at least for low-mass stars. The case is not yet clear for massive stars. The CO band head was also found by Hanson, Howarth, & Conti (1997) in the emission from massive stars in M17 in low-resolution spectra. Optical spectra of some of these same stars suggest they do have circumstellar disks.

The “$H$–$K$ excess” objects in NGC 3576 may be even younger than the M17 objects, which are visible in the $I$ band (Hanson et al. 1997) and are believed to be massive young stellar objects (YSOs), perhaps surrounded by a thick accretion disk. There are analogous massive objects with strong NIR excess in W31 (Blum, Damineli, & Conti 2001), W42 (Blum, Conti, & Damineli 2000), and W49 (Conti & Blum 2002).

Four sources, Nos. 48, 50, 60, and 60b (all sources with “No.” in the present paper follow the FBDC nomenclature), were found at the position of the MIR source IRS 1, identified by Frogel & Persson (1974). The $K$-band spectrum of No. 48 does not show any photospheric lines and moreover, No. 50 was not detected at $J$ and $H$ bands. For this reason no further information, such as spectral type could be derived from NIR data. However, at this evolutionary stage, crucial stellar parameters, including luminosity and hence the stellar mass, can be inferred by measuring their fluxes in the MIR. This spectral regime is also suitable to study the environment in which the YSOs are forming. The spatial distribution of dust can put constraints on the geometry of accretion since accretion via a disk needs large amounts of gas (which is mixed with the dust) concentrated in a small region.

NGC 3576 (also known as G291.3-0.71 or RCW 57) is a giant HII region located in the Galactic plane at a kinematic distance 2.8 (±0.3) kpc (FBDC). It was observed at radio wavelengths by McGee & Gardner (1968), Goss & Shaver (1970), Wilson et al. (1970), McGee & Newton (1981), and De Pree, Nysewander, & Goss (1999). Methanol masers were detected by Caswell et al. (1995) and water masers by Caswell et al. (1989). NIR photometry was performed by Moorwood & Salinari (1981), Moneti (1992), Persi et al. (1994), and FBDC, who presented a deep NIR study of NGC 3576. Frogel & Persson (1974) originally observed the region in the MIR. Five sources were identified, and the brightest, IRS 1, was unresolved with a $7''$ diaphragm. Later MIR observations of NGC 3576, from Moorwood & Salinari (1981), Lacy, Beck, & Geballe (1982), Persi, Ferrari-Toniolo, & Spinoglio (1987), and more recently, Walsh et al. (2001), were also unable to resolve the source IRS 1.

In § 2 of this paper we present high-resolution MIR observations of three selected fields in NGC 3576, taken through the atmospheric windows near 10 and 18 $\mu$m. The data and discussion of the results are presented in § 3. The conclusions are summarized in § 4.

2. OBSERVATIONS AND DATA REDUCTION

The data were obtained with the Gemini South Observatory 8 m telescope on 2001 November 30 and December 4 and 6, in service mode with the University of Florida OSCIR$^2$ MIR camera. The camera employs a Rockwell $128 \times 128$ pixel SI:As BIB detector, the plate scale at Gemini was 0.0859$''$/pixel$^{-1}$; the total field of view (FOV) of the array was $11'' \times 11''$.

Flux calibration was performed using the MIR standard star α CMa observed during the night as part of the baseline calibration program. Air-mass differences between the standard star observations and the target observations were $<0.3$ resulting in an uncertainty of approximately 10%. Table 1 presents a summary of the observations, as well as the filter parameters. Sky and background subtraction were achieved by the standard chop-and-nod technique. Sky images were taken $\sim 15''$ to the north of the selected fields. Images were processsed using the OSCIR reduction package running under the IRAF$^3$ environment, including the flat-field correction. The processed images were also corrected for bad pixels and finally were flux calibrated. The photometry was performed assuming a Gaussian point-spread function (PSF) model fitted to the objects.

Images were obtained through the $N$ broadband filter at 10.5 $\mu$m and the narrowband filters at 7.9, 9.8, 12.5, and 18.2 $\mu$m. The 40 s exposure time was the minimum value that allowed a complete chop-nod cycle. Based on precommissioning sensitivity, this value would result in a narrowband signal-to-noise ratio (S/N) of $\sim 3$ for a 100 mJy point source.

The detection limit (S/N $\sim 1$) is $\sim 100$ mJy in all bands, except at 18.2 $\mu$m, which is $\sim 900$ mJy. Three fields were

### TABLE 1

| Filter | Central Wavelength ($\mu$m) | Bandwidth ($\mu$m) | OSCIR ZMF/OS | OSCIR FD α CMa<sup>a</sup> | Observed PSF (arcsec) | Exposure<sup>b</sup> (s) |
|--------|---------------------------|------------------|--------------|--------------------------|----------------------|------------------|
| 7.9    | 7.91                      | 0.755            | 59.4         | 207.01                   | 0.4                  | 43               |
| 9.8    | 9.80                      | 0.952            | 39.9         | 138.03                   | 0.4                  | 43               |
| N      | 10.75                     | 5.23             | 37.8         | 131.82                   | 0.5                  | 40               |
| 12.5   | 12.49                     | 1.156            | 25.1         | 87.09                    | 0.4                  | 43               |
| HW18   | 18.17                     | 1.651            | 11.9         | 40.88                    | 0.65                 | 40               |

<sup>a</sup> Zero-magnitude flux density.

<sup>b</sup> Flux density of Sirius through OSCIR filters, assuming $N = -1.35$ mag and $Q = -1.34$ mag (Cohen et al. 1992).

<sup>c</sup> On-source integration time.

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2 This paper is based on observations obtained with the mid-infrared camera OSCIR, developed by the University of Florida with support from the National Aeronautics and Space Administration, and operated jointly by Gemini and the University of Florida Infrared Astrophysics Group.

3 IRAF is distributed by the National Optical Astronomy Observatory.
observed: the region associated with IRS 1 (in all bands), the region centered on No. 95 (at 7.9, 9.8, 12.5, and 18.2 \( \mu m \) bands), and the field in which Nos. 52 and 54 are located (only at the 12.5 \( \mu m \) band).

3. RESULTS AND DISCUSSION

The first field observed was centered at the position of IRS 1, where three NIR sources were found by Persi et al. (1994) and FBDC: Nos. 48, 50, and 60. The second field observed is located \( \sim 10' \) east of IRS 1. This field hosts two YSO candidates (Nos. 95 and 83) and a late-O/early-B star (No. 85) identified in the color-magnitude diagram presented by FBDC (their Figure 3). This second set of images, however, has a lower S/N, and for this reason we could only measure the flux for No. 95 in the 7.9, 9.8, and 12.5 \( \mu m \) bands. The third field was imaged only in the 12.5 \( \mu m \) band and for this reason will not be presented. It is located \( \sim 25' \) south of IRS 1 and hosts one YSO candidate (No. 52) and an object detected by FBDC only in the \( K \) band (No. 54). A third object was detected in this field as a negative pattern, its position relative to the extended emission seen at the top of image led us to identify this object as source No. 73, caught in the sky beam of the chopping procedure, 15\( '' \) north.

3.1. The Images

3.1.1. Nos. 48, 50, and 60

Sources in IRS 1 are presented in Figure 1. Panel \( a \) shows the \( K \)-band image of Nos. 48, 50, and 60 taken with the PHOENIX acquisition camera under good seeing (<0.3\( '' \)), the average PSF is \( \sim 0.35 \) and the camera plate scale is 0.0055 pixel\(^{-1}\).\(^4\) The sources are labeled according to FBDC. Figure 1\( b \) displays the \( N \)-band image of the same region showing the sources in IRS 1 resolved for the first time at 10 \( \mu m \) and identified with the NIR counterparts (again, adopting the source numbers of FBDC). The brightest MIR source is No. 50, followed by No. 48, the reverse of the situation seen in the \( K \)-band image, which shows No. 48 brighter than No. 50. For this reason, No. 48 was associated with IRS 1 by previous authors. Both images also show the double nature of No. 60. The companion of No. 60, hereafter No. 60b, is located \( \sim 0.4' \) away to the southwest. Like No. 50, it is brighter at longer wavelengths.

The images taken through the MIR narrowband filters are presented in Figure 2. Every image shows persistent artifacts located at the upper and lower right corners, produced by the chop-and-nod procedure. A careful inspection of the sky-beam images did not show any point-source object, however the artifacts could be produced by weak diffuse sources in the chopped sky beam. A logarithmic gray scale was used to emphasize the low-level extended emission in which the sources are embedded. The elongated shape in the north-south direction seen in the images at 7.9 and 12.5 \( \mu m \) (Figs. 2\( a \) and 2\( c \), respectively) was produced by non-optimum tuning of the primary mirror active optics system. A careful inspection of the images, especially the image taken at 9.8 \( \mu m \) (Fig. 2\( b \)), shows No. 60 elongated in the northeast-southwest direction. In this case, it is the effect of its near companion, as seen in the \( K \)-band image. It can be noted also that No. 60 is undetected in 7.9 and 12.5 \( \mu m \), but it is clearly seen in the 9.8 \( \mu m \) image. This brightening at 9.8 \( \mu m \) comes from the emission of dust silicate grains in low-density regions surrounding No. 60.

The case of Nos. 60b (\( N \)) and 60b (\( K \)) is somewhat different. Comparing the images taken at \( K \) and \( N \), we note that its centroid, relative to the centroid of other sources in the field, is shifted by \( \sim 0.2' \). Both images were supposed to be taken at the same orientation, but a slight rotation could lead to a mistake in the identification of the sources. The positions of the sources, relative to No. 50, are listed in Table 2. They were obtained from the astrometry of sources.

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\(^4\) See http://www.gemini.edu/sciops/instruments/phoenix/phoenixindex.html.
in Figure 1. The positions of all sources are the same (within the errors), except the position of No. 60b. This fact means that the $K$-band image has the same orientation as the $N$-band image. Therefore, we believe Nos. 60b and 60b ($N$) to be associated. This shifting in the positions represents $10^{16}$ cm at 2.8 kpc. This length scale is nearly the same as that expected for UC H II regions, which have radii up to $10^{16}$ cm and dust cocoons that are 10 times larger (Wood & Churchwell 1989b). We speculate that the positional shift is caused by emission and/or reprocessing of radiation arising from different places in No. 60’s dust cocoon. The $K$-band emission could be radiated by superheated dust grains located in a dense, self-protective accretion disk near the star (Churchwell 2002). On the other hand, radiation detected at longer wavelengths, such as the $N$ band, is emitted in the outer layers of the cocoon by warmer dust grains. The spatial resolution of both images, $\sim 0'.4$ (or $\sim 1.6 \times 10^{16}$ cm) is just high enough to make this effect evident.

### Table 2

| Source | $K$ | $N$ |
|--------|-----|-----|
|        | $\Delta$RA. | $\Delta$Dec. | $\Delta$RA. | $\Delta$Dec. |
| No. 48 | 1.0  | 1.5  | 1.0  | 1.5  |
| No. 60 | $-1.1$ | 1.8  | $-1.2$ | 1.8  |
| No. 60b| $-0.5$ | 1.5  | $-0.7$ | 1.6  |

Notes.—The coordinates are in arcseconds relative to No. 50, $\alpha = 11^h11^m33^s62 \delta = -61^\circ21'21''9''$ (J2000.0).

3.1.2. IRS 1:SE and No. 95

No. 95 is presented in Figure 3, a contoured mosaic in the 12.5 $\mu$m band built from the images taken at the positions of IRS 1 and No. 95. The level curves are in arbitrary units but a logarithmic scale was used to enhance the extended emission surrounding the sources. This figure is composed of two adjacent images with a small overlapping area. The positions of Nos. 83 and 85 are indicated for reference, as well as the position of a...
previously unknown MIR source, detected 8'' southeast of IRS 1. This source does not have any NIR counterpart to be correlated, so we named it IRS 1:SE. Images of No. 95 and IRS 1:SE are shown in the Figure 4; the extended emission seen around the sources comes from the warm dust distributed in the intracluster medium. No. 50 has a PSF FWHM that is statistically indistinguishable from that of the unresolved standard star. IRS 1:SE is an extended source but it has a prominent peak as intense as No. 95. For this reason and the fact that IRS 1:SE is located in the low-density end of the “tail” of the extended emission of No. 50, we believe that it is an embedded source instead of a bright knot in the cloud. The position of the peak emission is \( \alpha = 11^h 11^m 54^s 8 \) and \( \delta = -61^\circ 18' 26'' \) (J2000.0). No. 95, instead, closely resembles a cometary UC H II in the classification scheme of Wood & Churchwell (1989b).

3.2. Photometry

Photometry was performed by fitting a Gaussian PSF to the objects detected in the images, except IRS 1:SE. In this case the fluxes were obtained through a circular aperture of

Fig. 3.—Contoured mosaic of IRS 1 and No. 95 taken in the 12.5 \( \mu \)m band. The contour flux levels are in arbitrary units. A logarithmic scale was used to emphasize the extended emission around the sources.

Fig. 4.—Images of No. 95 at (a) 7.9 \( \mu \)m; contour levels are at 80 and 100 mJy; (b) 9.8 \( \mu \)m; the new MIR source IRS 1:SE is indicated; contour levels are at 2, 3, 4, and 6 mJy; (c) 12.5 \( \mu \)m; contour levels are at 3.5, 4, 5, and 8.7 mJy; (d) 18.2 \( \mu \)m; contour levels are at 25, 30, 40, 50, and 60 mJy.
1.5" radius centered at the peak of IRS 1:SE emission. The $N$-band flux extracted from the calibrated image is given in Table 3 along with NIR fluxes. The $JHK$ fluxes were calculated from the magnitudes reported by Figuerêdo (2001) and the $L$ flux is from Moneti (1992). The magnitudes were converted into fluxes adopting the zero points from Bessel & Brett (1988). SEDs in the range 1.25–18.2 $\mu$m are plotted in Figure 5. The SEDs show a flat spectrum for No. 48 and a spectrum rising toward longer wavelengths for No. 50. The 18.2 $\mu$m flux for Nos. 60 and 60b might be the fluxes of Nos. 60 and 60b together, since at this wavelength the sources remain unresolved.

Fluxes measured for each source at MIR wavelengths are presented in Table 4. The upper limits reported in this table (except for the Nos. 60 and 60b) represent the fluxes of the local background emission. They were obtained by integrating the flux of the extended emission at the position of the source over a circular aperture of 0.7. Therefore, they represent the minimum flux that the source indicated should have in order to be detected. The SEDs corresponding to the fluxes obtained with the narrowband filters are shown in Figure 6. The expected level of free-free MIR emission was obtained by extrapolating the 3.4 cm flux from De Pree et al. (1999), assuming $S_\nu \propto \nu^{-0.1}$, after deconvolving the $7' \times 7'$ radio beamwidth. The free-free emission represents 0.2% of the $N$-band flux of Nos. 48 and 60b, 0.02% for No. 50, 0.05% for No. 95, and 0.1% for IRS 1:SE.

While there is no reason to expect the standard classification of low-mass YSOs to be similar to that for high-mass YSOs, we can calculate similar spectral indices for the present sources to compare with those of lower mass stars. The 2.2–12.5 $\mu$m spectral indices $\alpha = d \log \nu F_\nu / d \log \nu$ (Lada 1987) for Nos. 48, 50, and 95, for which we have measured fluxes at 2.2 and 12.5 $\mu$m, are reported in Table 5. Nos. 48 and 50 have indices like a low-mass Class I object ($\alpha_{48} = 0.6, \alpha_{50} = 3.4$) and No. 95 has an index similar to a low-mass Class II object ($\alpha_{95} = -0.8$), according to the classification scheme of Greene et al. (1994).

The geometry of birth sites of these stars can explain the differences in the observed SEDs. It might be that the stars are surrounded by their birth material in the form of a torus seen at different lines of sight. The radiation escaping along the rotation axis would produce a dust-evacuated region, disrupting the spherical symmetric dust cocoons, and making them highly nonuniform in density. Therefore, the stellar luminosities derived from the fluxes reprocessed by the dust can be taken as lower limits only. Figure 7 is a sketch of this scenario. The light emitted by sources viewed edge-on or nearly edge-on is absorbed by the torus, consistent with deep dust absorption observed at 9.8 $\mu$m and little or no emission at wavelengths shorter than 10 $\mu$m. However, the emission of superheated dust grains in the inner radius of the torus (seen as white) could be detected in the $K$ band if it is not seen exactly edge-on. This would be the case for No. 50. From above (or below) the torus equatorial plane, the light emitted by the star would travel through regions with lower density, implying lower absorption by the dust. From this viewpoint, the light emitted at NIR wavelengths (\leq 2.2 $\mu$m) could be detected, but photospheric lines would appear veiled by the inner torus emission. The CO band head at 2.3 $\mu$m is detected in emission if the angle is small (the case for No. 48), otherwise it would be detected in absorption (as we see in the spectra of the YSO candidates Nos. 4, 160, and 184, for which we do not yet have any MIR data). Increasing the angle over (or below) the equatorial plane, one would observe the radiation that crosses regions with even lower densities (Fig. 7, grey volume around the torus), in this case the dust absorption feature is absent and the star becomes brighter at wavelengths shorter than 2 $\mu$m. This would be the scenario for Nos. 95 and 60. Even at this vantage point, the photospheric lines would still appear veiled by the inner torus emission and/or by radiation reflected by the lower density dust near the star.

### 3.3. Color Temperature, Luminosity and Silicate Absorption

Observations at two different wavelengths can be combined to determine the dust color temperature and optical
depths (Ball et al. 1996; De Buizer 2000). Since temperature determines the ratio of blackbody flux densities at any two wavelengths, color temperature maps can be obtained by simply ratioing two calibrated images at different wavelengths.

The dust color temperature of sources in the field of IRS 1 was obtained from the ratio of images taken at 7.9 and 18.2 \( \mu \text{m} \). Both images were registered by matching the position of No. 50 and enlarged to show the sources; the resulting image is shown in the Figure 8. Nos. 50 and 48 are clearly seen and they have color temperatures of \( \sim 280 \pm 10 \) and \( \sim 215 \pm 15 \) K, respectively. Nos. 60 and 60b are not detected in this map because of their low S/N.

The dust color temperature of No. 95 and IRS 1:SE were also obtained, but in this case through the fluxes measured in the 12.5 and 18.2 \( \mu \text{m} \) band, since the image taken at 7.9 \( \mu \text{m} \) has low a S/N. The results are \( T = 270(\pm10) \) K for No. 95, \( T = 100(\pm20) \) K for IRS 1:SE. The uncertainties in the temperatures represent the difference between the results obtained using the 7.9/18.2 \( \mu \text{m} \) flux ratio and the 12.5/18.2 \( \mu \text{m} \) flux ratio.

The MIR luminosities of Nos. 48 and 50 were estimated by integrating the fluxes measured at 3.5 (\( \text{L-band} \)), 7.9, 12.5, and 18.2 \( \mu \text{m} \). The MIR luminosity of No. 60b was instead estimated by performing the same integration, but using only the fluxes measured at 7.9, 12.5, and 18.2 \( \mu \text{m} \). From these results, we can estimate the bolometric luminosity assuming that the MIR luminosity must represent \( \sim 10\% \) of the bolometric luminosity (Wood & Churchwell 1989a). The results are presented in Table 5. The spectral types were obtained from the derived bolometric luminosities and the grids of stellar models of Schaller et al. (1992), and they should be considered approximate given the large bolometric correction used to derive the bolometric luminosity.

The silicate absorption map can be used to investigate the spatial distribution of dust, and it was obtained by ratioing the 9.8 \( \mu \text{m} \) band image and a “continuum” image. This continuum was produced by averaging the images at 7.9 and 12.5 \( \mu \text{m} \). The silicate optical depth, obtained by the procedure described by Gezari, Backman, & Werner (1998), is

![Figure 6](image-url)  
**Fig. 6.**—Narrowband MIR spectral energy distribution of sources in NGC 3576. Shown are Nos. 48 (squares), 50 (circles), and 60 (diamonds), as well as IRS 1:SE (upward-facing triangles; in Jy arcsec\(^{-2}\) for this extended source) and No. 95 (downward-facing triangles). The arrow at 7.9 \( \mu \text{m} \) is the upper limit of IRS 1:SE, and it is connected to the upward triangle. The arrow at 18.2 \( \mu \text{m} \) is the upper limit of source 60b.

![Figure 7](image-url)  
**Fig. 7.**—Schematic of the geometry of birth material surrounding the detected sources. Viewing such a source from different lines of site could produce the different observed SEDs for the NGC 3576 objects. The torus is flared because of the action of strong stellar winds (Hollenbach et al. 1994). The inner radius of a typical dust shell is \( \sim 10^{16} \) cm and the outer radius is \( \sim 10^{18} \) cm (Churchwell, Wolffe, & Wood 1990; Faison et al. 1998). Superheated dust grains can survive in the self-protective inner regions of the torus at radii smaller than \( 10^{16} \) cm. The drawing is not to scale; see text for details.
$\tau_{g,8} = 3.7$ for No. 50, corresponding to $A_V = 59$ mag, assuming $A_V = 16 \times \tau_{g,8}$ (Rieke & Lebofsky 1985) and $\tau_{g,8} = 0.77$ for No. 48 corresponding to an $A_V = 12$. Previous estimates of the opacity of IRS 1 are from Persson, Frogel, & Aaronson (1976), who found $\tau_{g,8} = 3.5$ using a 15" beamwidth and from Persi et al. (1994), who found $\tau_{g,8} \approx 4.7$, using a circular variable filter 10 µm spectrum taken with an aperture of 7".5. Both estimates were made using large apertures, which include contributions from all sources and also their surrounding dust. Values for visual extinction obtained with NIR data for No. 48 are $A_V = 14.3$ (FBDC) and $A_V = 11$ (Persi et al. 1987).

### 3.4. Where Is the Ionizing Source of NGC 3576?

IRS 1 was initially thought to be an important source of radiation for NGC 3576, but we have found that it does not contribute substantially, as we show below. The number of Lyman continuum photons derived from the radio data (De Pree et al. 1999) is $\sim 10^{50}$ s$^{-1}$ for NGC 3576. A single O3 star or a cluster of at least 10 O6 stars is needed to produce the amount of Lyman continuum photons found in NGC 3576, but where are the ionizing sources? Figure 9 gives us an idea. The K-band image of NGC 3576, from FBDC, was overplotted by the 3.4 cm continuum contour curves, from De Pree et al. (1999). The radio beamwidth in the image is 7". X-ray YSOs are shown inside the circles and the positions of MIR sources, detected by Persson et al. (1976), are shown as boxes. None of the MIR sources (IRS 1–5) is associated with the radio peak emission, moreover IRS 1 does not affect the level curves in its vicinity. However, the strong continuum emission and rather large beam size of the radio image may be limiting our ability to detect compact radio emission around the IRS 1 source. The radio data neither eliminate nor preclude their presence. However, according to our torus model and expectations for the evolutionary status of the massive YSOs outlined in § 1, we expect that these sources might be in the UC H II region phase. Despite the lack of a compact 3.4 cm source, there is very strong Br\alpha emission surrounding the IRS 1 sources (R. D. Blum 2003,

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**TABLE 5**

| Source | $T_c$ (K) | $L_{\text{MIR}}$ (ergs s$^{-1}$) | $\log L/L_{\odot}$ | Spectral Type (ZAMS) | Spectral Index |
|--------|----------|-----------------------------|-------------------|---------------------|---------------|
| 48     | 215 (±10) | $2.7 \times 10^{36}$       | 3.8               | B1                  | 0.6           |
| 50     | 280 (±10) | $2.4 \times 10^{37}$       | 4.8               | O8                  | 3.4           |
| 60b    | >100$^b$  | $3.5 \times 10^{35}$       | 2.9               | B3                  | ...           |
| 95     | 270 (±15) | $1.5 \times 10^{36}$       | 2.5               | B5                  | -0.8          |

$^a$ Bolometric luminosity estimated by adopting a “bolometric correction” as given by Wood & Churchwell 1989a for UC H II regions, $L = 10 \times L_{\text{MIR}}$, see text.

$^b$ Lower limit for the temperature due to the unresolved nature of the source at 18.2 µm.

$^c$ The MIR luminosity is an upper limit based on the upper limit to the flux in the 18 µm band. See Table 3.

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*Fig. 8.—(a) Color temperature map of the ratio of the 7.9 and 18 µm images. The contours are at 160, 180, ..., 280 K. (b) Map of the optical depth of the silicate absorption feature at 9.8 µm. The darker regions exhibit the strongest absorption. The rounded contour at the position of No. 60 marks where the absorption turns into emission. In both images “A” indicates an artifact produced by the low S/N at this position after ratioing the images.*
private communication). This strongly suggests a local contribution to the ionization of the circumstellar environment of these objects. For the brightest K-band source, No. 48, we have recently obtained a high spectral resolution ($R = 50,000$) spectrum at 2.17 $\mu$m on the Gemini South telescope, which shows a marked double-peaked morphology. This morphology does not include broad wings typical of a disklike signature, but it would be consistent with a shell or torus geometry. This spectrum (to be published in an upcoming paper) is consistent with our torus model, and we thus prefer the interpretation that the IRS 1 sources are in an UC H II region phase, rather than in an earlier phase of evolution.

Returning to the issue of where the dominant ionizing sources in NGC 3576 lie, we note that the radio peak emission corresponds to a region of dark patches to the south in the K-band image, and for this reason no ionizing source(s) could be detected at K. The radio peak emission lies far from any MIR source and it is identified as an UC H II region in Figure 2f of Walsh et al. (2001). The ionizing source(s) must be a stellar cluster, just blocked by the dark clouds in the line of sight. In this case the cluster stars must be somewhat evolved: they have already broken out of their birth material, producing the quoted Lyman continuum photons that are ripping apart the intervening dark patches and hence do not form any detectable UC H II region. If the stars in the cluster were in an earlier, more enshrouded stage of evolution, they could not produce the observed radio emission. A complete MIR map of the region is planned in order to further study the massive YSO candidates and their environment on the same basis as we have done for IRS 1.

4. SUMMARY AND CONCLUSIONS

We have presented MIR images of NGC 3576. IRS 1 is resolved into four sources for the first time at 10 $\mu$m. The brightest source in the N band is No. 50, which is different from the situation seen in the K band, where No. 48 is the brightest. We have also presented MIR images of the YSO candidate No. 95, the detection of NIR sources Nos. 52 and 54, and No. 73 as a negative object in the sky beam.

SEDs of Nos. 48, 50, and 60 were constructed from 1.25–18.2 $\mu$m by combining the data available in the literature with our data. We also constructed the MIR SEDs for Nos. 48, No. 50, 95, and the detected companion of No. 60, named No. 60b, based on the fluxes measured through narrowband filters.

The optical depth, and hence the visual extinction toward each object was obtained from the silicate absorption feature and amounts to $\tau_{silic} = 3.7$ ($A_V = 59$ mag) for No. 50 and $\tau_{silic} = 0.77$ ($A_V = 12$ mag) for No. 48. Previous values of visual extinction for No. 48 are $A_V = 14$ (FBDC) and $A_V = 11$ (Persi et al. 1987).
The MIR luminosity of Nos. 48, 50, 60b, and 95 were obtained after integrating their MIR fluxes in order to give an approximation of their bolometric luminosities and hence the spectral types. We argue, based on the radio continuum image, that the IRS 1 sources are not the major contributors to the ionization of NGC 3576. Nevertheless, we conclude that Nos. 48, 50, and 95 are young massive stars possibly surrounded by a torus of gas and dust which is responsible for the different SEDs observed.

We report the detection of a new diffuse MIR source without any NIR counterpart. This source was found at 8° southeast of No. 50 and has a core-halo morphology. We named it IRS 1:SE and derived the color temperature of $\frac{C_24}{C_100}$ K. IRS 1:SE has both morphology and color temperature compatible with HCs (Osorio et al. 1999). Moreover, its emission profile is indistinguishable from a point source embedded in extended emission. For these reasons we do not believe that IRS 1:SE is just a bright knot in the tail of the extended emission of No. 50. However, additional data are needed to give any firm conclusion.

The ionizing source of NGC 3576 is believed to be behind the dark clouds seen in the $K$-band image, blocked from detection at shorter wavelengths by large amounts of intervening dust.

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