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Thermal dust imaging of the cometary HII region NGC 6334 F*

Paolo Persi[1], **Mauricio Tapia**[2], **Marcello Felli**[3], **Pierre Olivier Lagage**[4], **and Marco Ferrari-Toniolo**[1]

[1] Istituto Astrofisica Spaziale, Area di Ricerca Roma-Tor Vergata, Via del Fosso del Cavaliere, I-00133 Roma, Italy
[2] Instituto de Astronomia, UNAM, Apartado Postal 877, Ensenada, 22830, B.C., Mexico
[3] Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
[4] CEA/DSM/DAPNIA/, Service d'Astrophysique (URA 2052 du CNRS), CE Saclay, F-91191 Gif-sur-Yvette, France

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Abstract. Sub-arcsec images at 3.8 and 11.2 μm of the cometary HII region NGC 6334 F are presented. Only the HII region is detected at 3.8 μm, while three distinct small diameter sources and a diffuse extended emission are found at 11.2 μm. The brightest of the small diameter sources (called MIR 2) is coincident with the HII region. MIR 2 is resolved and shows a cometary shape similar to that observed in the radio continuum. This suggests that warm dust and ionized gas are well mixed in the HII region. The diffuse extended emission is observed in the region where the highest density molecular gas and the central region of the molecular outflow are located. No emission at either wavelength is detected from IRS-I 2, the proposed alternative powering source of the bipolar molecular outflow.

Key words: ISM: HII regions – ISM: individual objects: NGC 6334 F – ISM: jets and outflows – infrared: stars

1. Introduction

NGC 6334 F (following the radio nomenclature of Rodríguez et al. 1982) is an ultra compact (UC) HII region totally obscured optically and detected at radio wavelengths (Rodríguez et al. 1982). It is located near the northern end of a chain of star forming complexes detected in the FIR, at the position of component I (roman one, following the FIR nomenclature of McBreen et al. 1979). In the radio continuum it has a cometary morphology (Rodríguez et al. 1982; De Pree et al. 1995, Carral et al. 1997) with a steep brightness gradient toward the northwest, i.e. in the direction facing a high density molecular cloud detected in HC_3N (Bachiller & Cernicharo 1990), NH_3(1,1) (Jackson et al. 1988), and NH_3(3,3) (Kraemer & Jackson 1995). The UC HII region must be excited by a massive star as deduced from the luminosity of the mid-IR source (IRS-I 1) associated with it (Harvey & Gatley 1983) and the number of UV photons required to ionize the nebulosity (Rodríguez et al. 1982). Persi et al. (1996) have shown with J, H and K images that IRS-I 1 has a complex structure in the near-IR, with at least four very red components all within a circle of 4″ in diameter.

The NH_3(1,1) gas shows two distinct spatial components aligned in the NE–SW direction and placed on both sides of the HII region (Jackson et al. 1988). Their velocities are separated by more than 3 km s^{-1} and the velocity pattern was interpreted by Jackson et al. (1988) as evidence for a molecular disk in keplerian rotation around a massive star (presumably IRS-I 1, the ionizing star of the HII region). However, observations of CO(2-1) by Bachiller & Cernicharo (1990) showed a well collimated high-velocity CO bipolar outflow (with terminal velocity of 70 km s^{-1}) exactly in the same direction. This was in evident contrast with the expected direction of the toroid (i.e. perpendicular to the outflow axis) and led Bachiller & Cernicharo (1990) to reinterpret the NH_3(1,1) observations as the low velocity part of the bipolar outflow (see also De Pree et al. 1995). Subsequently, the bipolar outflow interpretation was further confirmed by the detection of NH_3(3,3) maser emission at the two heads of the CO lobes (Kraemer & Jackson 1995) and of shocked H_2 emission at the same position (Persi et al. 1996).

According to Bachiller & Cernicharo (1990) the bipolar outflow and the ionization of the HII region originate from the same star, namely that associated with IRS-I 1. Alternatively, De Pree et al. (1995), proposed that IRS-I 1 coincided with the early type star that provides the UV photons ionizing the HII region, and that a second source (IRS-I 2), 6″ to the northwest and detected at 20 and 30 μm by Harvey & Gatley (1983), could be the stellar source at the origin of the bipolar outflow. In fact, the outflow axis seems to pass slightly to the NW of the sharp ionization front. The hypothesis of two distinct early type stars was further reinforced by the detection of a weak unresolved 7 mm source just beyond the edge of the cometary ultracompact HII region (which is by far the strongest source at 7 mm with a flux density of almost 3 Jy compared to a flux density of 26±7 mJy for the weak unresolved component), roughly 2″ south of IRS-I 2 (Carral et al. 1997). The spectral index of the weak unresolved 7 mm source (actually a lower limit, since the source is not detected at longer wavelengths) indicates that the emission must come from heated dust surrounding a protostar, suggesting the presence ahead of the blister of a protostar in an even earlier evolutionary phase with respect to the UC HII region. However,

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Send offprint requests to: P. Persi, (persi@saturn.ias.rm.cnr.it)

* Based on observations obtained at CFHT and UKIRT on Maona Kea.

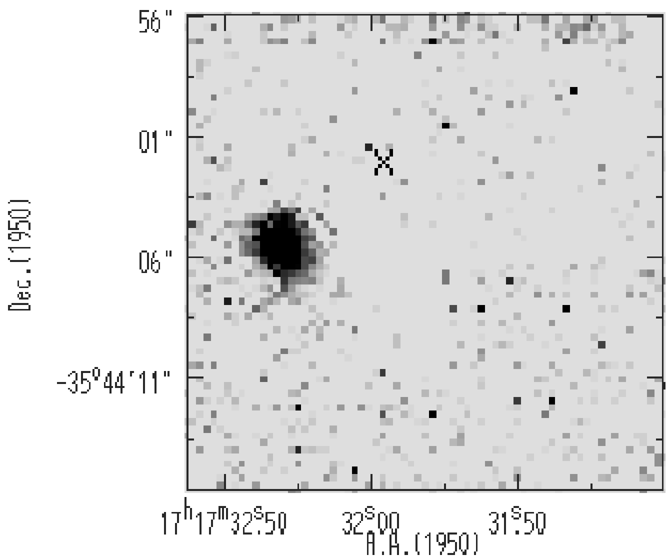

Fig. 1. L'-band image of NGC 6334 F. The area imaged is 19.7×19.7 square arcsec. The cross indicates the position of IRS-I 2.

no near IR source was detected at the position of IRS-I 2 (Persi et al. 1996). The near IR source # 48 (Tapia et al. 1996) located within 1″ of the 7 mm clump most probably is a foreground highly reddened B4-A2 star, unrelated to the 7 mm clump.

An H_2O maser is present in this star forming complex. The accurate position of Forster & Caswell (1989) (see also note in the caption to Fig. 1 of Carral et al. 1997) associate it with IRS-I 1, while no H_2O maser is reported from the position of IRS-I 2.

In order to identify the driving source of the molecular outflow and to study in more detail the circumstellar material surrounding IRS-I 1, we have obtained high spatial resolution thermal images of NGC 6334 F in the L'-band (3.8 μm) and at 11.2 μm . Our observations show that IRS-I 1 has an extended structure at 11.2 μm with a blister morphology similar to that seen in the radio. We find two additional small diameter sources and an extended diffuse emission at the position of the molecular cloud at 11.2 μm, but we do not detect any small diameter mid-IR source at the position of IRS-I 2 or of the 7 mm unresolved clump.

2. Observations and data reduction

The L'-band and 11.2 μm direct images of NGC 6334 F were obtained with UKIRT and CFHT on Mauna Kea on February and July 1996, respectively.

For the L'-band IRCAM3 mounted on UKIRT was used, equipped with a 256×256 InSb array and with a scale of 0.29 ″/pix. The observation was made at dawn with no secondary mirror chopping. To achieve rapid sky subtraction, the telescope was nodded with an amplitude of $\sim$ 20″ after each 6.5 sec integration, achieving a total on-source integration time of 468 sec. No standard stars were observed to calibrate the image. A rough calibration was obtained using the L'-band photometry of IRS-I 1 taken with an aperture of 5″ by Becklin & Neugebauer (1974).

The narrow–band image at 11.2 μm ($\Delta\lambda$ = 0.44 μm) was obtained with the mid–IR camera CAMIRAS developed at the Service d'Astrophysique at Saclay (Lagage et al. 1992), equipped with a 192×128 Si:Ga/DVR detector array, and mounted at CFHT(Canadian-French-Hawaii Telescope). We used a scale of 0.31″/pix and the measured point-spread function was of $\sim$ 1″. The observations were made in chopping and nodding mode in order to subtract the sky and the telescope emissions. The standard stars γ Aql and η Sgr were observed at approximately the same air mass to calibrate the image of NGC 6334 F. The astrometry of the 11.2 μm image was made comparing it with the K image with similar spatial resolution obtained by Persi et al. (1996). Figs. 1 and 2 show the L'-band and the 11.2 μm images of NGC 6334 F.

Given the low sensitivity of the L'-band image, only IRS-I 1 was observed, though with a "cometary" shape (Fig. 1), while in the 11.2 μm image (Fig. 2) this source (here named MIR 2) and other two point-like sources (all found in the near–IR by Tapia et al. 1996) as well as diffuse emission extending west of IRS-I 1 were detected. The estimated flux density at 11.2 μm for the diffuse emission is $\sim$ 14 Jy.

In Table 1 we report the positions and the flux densities at 11.2 μm of the detected sources. The flux density of MIR 2 (IRS-I 1) is relative to an aperture of 10″ in radius.

In order to study in detail the morphology of this source we have applied to the 11.2 μm image, the Lucy-Richardson spatial enhancement algorithm developed by Richardson (1972) and Lucy (1974). This treatment is based on a good spatial sampling of the point-spread-function and the high signal-to-noise ratio of the raw data. Both requirements are satisfied for our image. With this algorithm, we can obtain a resolution of $\sim$ 0.4″. The contour map of the deconvolved 11.2 μm image of NGC 6334 F is reported in Fig. 3. MIR 2 (IRS-I 1) appears to be resolved with an effective FWHM size of $\sim$1.2″ (2090 AU, $\sim$ 3 10^{16} cm at d = 1.74 Kpc) and contains approximately 80% of the total flux reported in Table 1.

Finally, the images of Figs. 1 and 2 do not show any mid–IR source at the position of IRS-I 2 (indicated with a cross in the figures). The upper limits for a point source are 0.08 and 1.2 Jy (1 σ) at 3.8 and 11.2 μm, respectively. Although the sensitivity at 11.2 μm is high ($\sim$25 mJy/arcsec^2), the rather large value of the upper limit is due to the fact that IRS-I 2 is located within the diffuse emission (see Fig. 2).

3. Discussion

Most of the discussion reported here relates to the analysis of the 11.2 μm image, given its higher sensitivity and spatial resolution.

All the mid-IR sources reported in Fig. 2 have been detected in the near–IR by Tapia et al. (1996), and their identification is given in Table 1, column 5. MIR 1 is immersed in the diffuse emission extending in the direction of the molecular cloud-bipolar outflow. A second point-like source, not reported

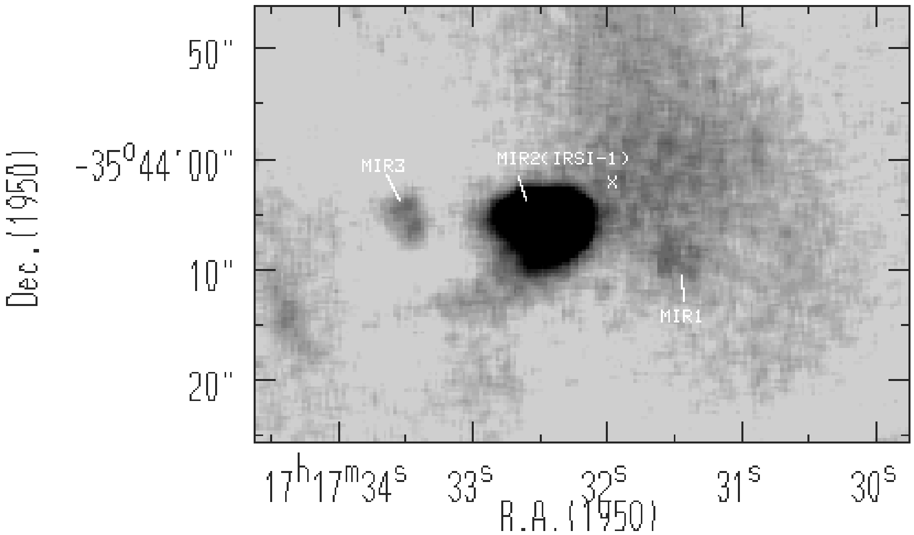

Fig. 2. 11.2 μm image of NGC 6334 F. The area imaged is 59.5×39.7 square arcsec. The cross indicates the position of IRS-I 2.

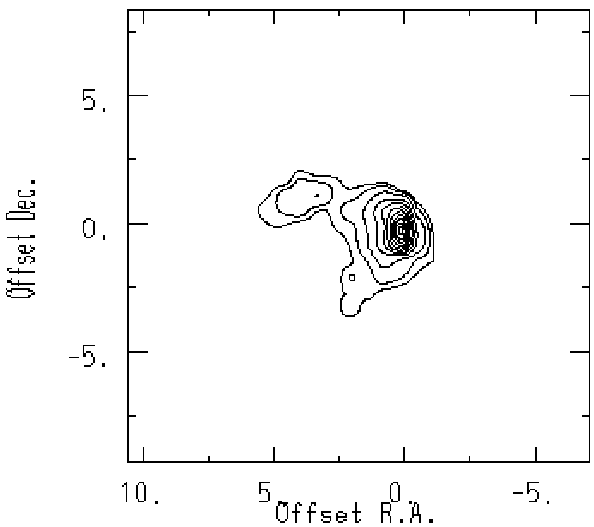

Fig. 3. Contour levels of the deconvolved 11.2 μm image of NGC 6334 F. The origin of the coordinates is at α(1950) = 17^h 17^m 32.3^s; δ(1950) = -35° 44′ 05.5″

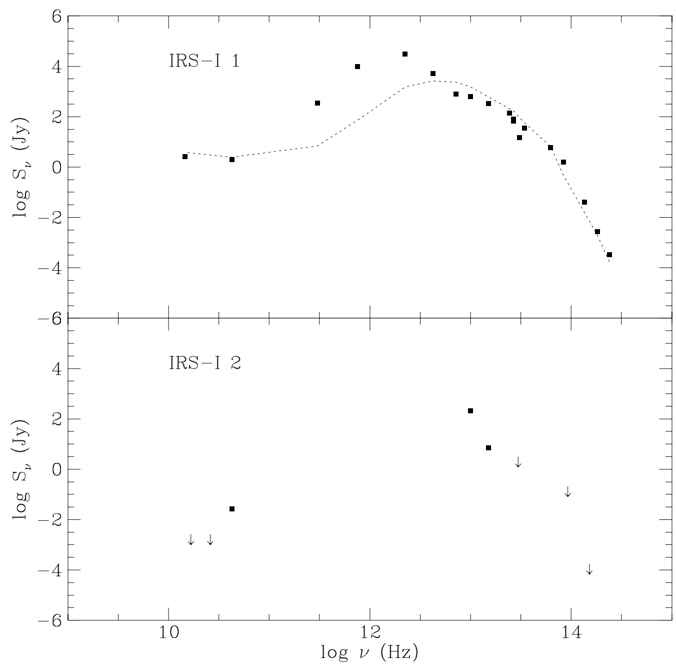

Fig. 4. Infrared flux distribution of IRS-I 1 (upper panel), and IRS-I 2 (lower panel). References for the observed flux densities are: J, H and K, Tapia et al. (1996); L and M, Persi& Ferrari-Toniolo (1982); from 8.7 to 30 μm, Harvey & Gatley (1983) and this work; 42–134 μm, Loughran et al. (1986); 400 μm, Gezari (1982); 1 mm, Cheung et al. (1978); 7 mm, Carral et al. (1997); 2 and 6 cm, De Pree et al. (1995). The dashed line represents the model "H" of dusty HII regions of Natta & Panagia (1976).

Table 1. Positions and flux densities of the small diameter 11.2 μm sources observed in NGC 6334 F

Source	α(1950) h m s	δ(1950) ° ′ ″	Flux (Jy)	Id.	Ref.
MIR1	17 17 31.7	-35 44 08.9	2.3(0.2)	#31	a
MIR2	17 17 32.3	-35 44 05.5	79(6.3)	IRS-I 1, #46	a, b
MIR3	17 17 33.6	-35 44 05.1	1.8(0.2)	IRS-I 3, #41	a, b

References: a) Tapia et al. (1996), b) Harvey & Gatley (1983).

in Table 1 and identified with the near-IR source #68 (Tapia et al. 1996) and St 11 (Strow et al. 1989), has been detected within the cloud at the limit of the diffuse emission.

The source MIR 3 coincides with IRS-I 3 of Harvey & Gatley (1983), and appears sligthly extended, as is also observed in the K-band image of Persi et al. (1996). Combining the 2.2 and 11.2 μm flux densities we derive for this source a spectral index n = dLog (ν F_ν)/ dLog ν = - 2.2, typical of very young stellar objects, with an IR luminosity of a B0 ZAMS stars. In fact, its JHK colors show very strong excess at 2 μm (Tapia et al. 1996).

We have obtained the integrated flux distribution of MIR 2 (IRS-I 1) combining observations from the near-IR to the radio continuum taken from the literature as well as those presented

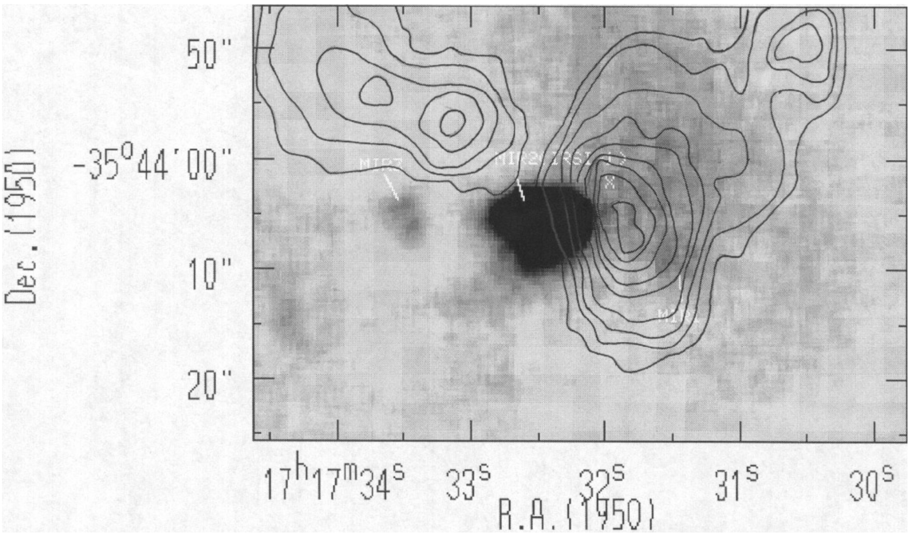

Fig. 5. The integrated NH_3 (1,1) main hyperfine line emission detected by Jackson et al. (1988) is superposed on the 11.2 μm image

in this work (Fig. 4, upper panel). This continuum flux density distribution is very similar to those of UC HII regions studied by Wood & Churchwell (1989), in which thermal emission from dust heated by a central star accounts for nearly all the radiation at wavelengths less than ∼1 mm. A color temperature of T[11.2-20] ∼130 K has been derived from our observed 11.2 μm flux density and the 20 μm flux density of Harvey & Gatley (1983). In addition, Fig. 4 shows that the 7 mm and 2 cm emission are due to optically thin free-free emission from the ionized gas surrounding IRS-I 1. This free-free emission could contribute also to the nebulosity observed at 2.2 μm by Persi et al. (1996) as can be seen extrapolating the 7 mm flux density to 2.2 μm with a law of the type $S_\nu \propto \nu^{-0.1}$. The flux distribution has been compared with model "H" of dusty HII regions developed by Natta & Panagia (1976) (dashed line in Fig. 4). This model, computed for a uniform spherical nebula composed of gas and two types of grains and with a central empty cavity surrounding an early type star, fits quite well the flux distribution in the near, mid–IR and radio region of the spectrum. The discrepancy with the far-IR, 400 μm and 1 mm spectral points may be due to the fact that these observations have been obtained with a much larger beam compared with the other observations.

The morphology of MIR 2 is best seen in the deconvolved map shown in Fig. 3. An arcuate or cometary apparence is present, with two knots of emission. The brightest peak is coincident with IRS1E, the reddest near IR-source of IRS-I 1 (Persi et al. 1996). This source appears resolved with a size of $\sim 3\ 10^{16}$ cm (see Sect. 2), similar to that observed in the radio continuum by Rodríguez et al. (1982) ($\sim 6\ 10^{16}$ cm). Comparing the 11.2 μm image with the radio continuum map at 2 cm obtained with similar resolution by De Pree et al. (1995), we conclude that the warm dust in NGC 6334 F is either inside or at the outer boundary of the ionization front, as also observed in the cometary UC HII region G29.96-0.02 (Ball et al. 1996). A second knot of emission is present approximately 4″ east and 1.3″ north of IRS1E.

Assuming that the ionizing star in NGC 6334 F is an O8 ZAMS (L $\leq 8\ 10^4\ L_\odot$ Harvey & Gatley 1983), we have derived a dust temperature $T_d \sim 105$ K at a distance of $3\ 10^{16}$ cm from the central star applying the model of Churchwell et al. (1990). This temperature is in agreement with the color temperature derived by the IR spectral points.

MIR 2 (IRS-I 1) coincides with IRAS 17175-3544, whose color-corrected flux density at 12 μm is 115 Jy. This value is consistent with that observed at 11.2 μm, including the contribution of all the three sources (MIR 1,2,3) and the diffuse emission.

The 11.2 μm diffuse emission extends towards the dense core of the molecular cloud, as clearly shown by the overlay of the integrated thermal NH_3 (1,1) line emission (Jackson et al. 1988) with the 11.2 μm emission of Fig. 5, and could be either due to externally heated dust, or to polycyclic aromatic hydrocarbons emission (PAH's). In fact, spectrophotometric observations of the HII region/neutral interface in M17 obtained with ISOCAM by Cesarsky et al. (1996), indicate that the extended emission is dominated by PAH's. A similar interpretation has been given by Minchin et al. (1992) to explain the extended IR emission in the CepB-S155 interface region.

As far as IRS-I 2, using our quoted upper limits (for a point source), the 20 and 30 μm flux densities taken from the contour maps of Harvey & Gatley (1983) and the 7 mm flux density of Carral et al. (1997), assuming they arise from the same object, we have derived the flux density distribution shown in Fig. 4, lower pannel. Considering that at a level of 1.2 Jy we do not detect any source at 11.2 μm coincident with the 7 mm clump reported by Carral et al. (1997), it is improbable that this clump, if confirmed, has a hot internal stellar source heating it from the inside. In fact, emission from hot dust around an early type star (e.g. an O9.5 with luminosity $\geq 3\ 10^4\ L_\odot$, following Harvey & Gatley 1983), with temperature in the range 200–1000 K should be easly detectable at 11.2 μm unless the extintion has a very high value, $A_V \geq 110$–140. Without further observations of this clump at millimeter and submillimeter wavelengths, little can be said about its nature. There is also the possibility that the 20 and and 30 μm flux densities of IRS-I 2 (Harvey & Gatley 1983) might be contamined by the extended diffuse emission observed at 11.2 μm and associated with the molecular cloud.

With respect to the model presented by Testi et al. (1998) to put the different objects found in the star forming complex G9.62+0.19 into a consistent evolutionary sequence, MIR 2 (IRS-I 1) is clearly the one in a more evolved phase. The ionized gas is clearly detectable in the radio continuum, the cluster of early type stars embedded in the HII region can be seen in the near-IR and the warm dust emission can be seen at longer wavelengths. The H_2O maser is located in between IRS1E and the sharp ionization front. This phase is comparable to component B in G9.62+0.19 or even earlier, given the presence of the H_2O maser and the compactness of the HII region. MIR 3 seems to be in an earlier stage in which the hot dust emission around the early type star is well detectable in the near and middle-IR, but the radio continuum emission from a possible HII region is still not detectable, most probably for self-absorption effects in these early stages. This phase is not dissimilar to component F in G9.62+0.19 or even earlier given the lack of H_2O maser. Finally, IRS-I 2, not detected in the present observations or in the near-IR but possibly only at 7 mm and (if not confused) at longer IR wavelengths, could represent an even earlier stage, in which only the cold dust emission is detectable and no early type star has been formed yet inside the clump. It would be of extreme interest to know if molecular outflow can be produced in such early phases, but to confirm the association of IRS-I 2 with the molecular outflow (and its true nature), higher resolution observations at 20 - 30 μm as well as improved VLA observations of the 7mm clump are needed.

4. Conclusions

From the analysis of the high spatial resolution mid infrared images of the cometary HII region NGC 6334 F we can make the following conclusions:

1) Three mid–IR sources and an extended diffuse emission, are present in the 11.2 μm image.

2) The source MIR 2 (IRS-I 1) coincident with the HII region, is resolved with a size of approximately 3-6 10^{16} cm. The flux distribution of this source (Fig. 4) indicates that the 11.2 μm emission is due to a circumstellar dust at $T_d \sim$ 105-130 K. Its morphology and size are similar to the diffuse emission observed at 2.2 μm and in the radio continuum. This suggests that the dust and gas are well mixed inside the HII region or just at the edge of the ionization front.

3) The source MIR 3 located east of the HII region is identified with the source IRS-I 3 of Harvey & Gatley (1983) and shows a spectral index n = - 2.2, typical of very young stellar objects. Lack of radio continuum emission places this source in an earlier evolutionary stage with respect to MIR 2 (IRS-I 1).

4) A very diffuse 11.2 μm emission is observed in the densest part of the molecular cloud (Figs. 2 and 5) west of the HII region, where the CO bipolar molecular outflow is also located. A plausible explanation for the emission comes from PAHs in the molecular cloud.

5) Because of this diffuse emission we cannot confirm the presence of the very cold (presumably unresolved) object IRS-I 2 that has been suggested as the driving source of the bipolar outflow. We can only exclude that the 7 mm clump is heated by an internal early type star unless the extinction is so high ($A_V \geq$ 110–140) to inhibit detection at 11.2 μm of the hot dust envelope surrounding the early type star. High resolution images at longer wavelengths (20 μm or submillimeter) as well as a better definition of the bipolar outflow center are needed to establish which is the energy source of the bipolar outflow.

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