

Triggered star formation and Young Stellar Population in Bright-Rimmed Cloud SFO 38

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ABSTRACT

We have investigated the young stellar population in and around SFO 38, one of the massive globules located in the northern part of the galactic H II region IC 1396, using the *Spitzer* IRAC and MIPS observations (3.6 to 24 μm) and followed up with ground based optical photometric and spectroscopic observations. Based on the IRAC and MIPS colors and H α emission we identify ~ 45 Young Stellar Objects (Classes 0/I/II) and 13 probable Pre Main Sequence candidates. We derive the spectral types (mostly K- and M-type stars), effective temperatures and individual extinction of the relatively bright and optically visible Class II objects. Most of the Class II objects show variable H α emission as well as optical and near-infrared photometric variability which confirm their “youth”. Based on optical photometry and theoretical isochrones, we estimate the spread in stellar ages to be between 1–8 Myr with a median age of 3 Myr and a mass distribution of 0.3–2.2 M_{\odot} with a median value around 0.5 M_{\odot} . Using the width of the H α emission line measured at 10% peak intensity, we derive the mass accretion rates of individual objects to be between 10^{-10} to 10^{-8} M_{\odot}/yr . From the continuum-subtracted H α line image, we find that the H α emission of the globule

is not spatially symmetric with respect to the O type ionizing star HD 206267 and the interstellar extinction towards the globule is also anomalous. We clearly detect an enhanced concentration of YSOs closer to the southern rim of SFO 38 and identify an evolutionary sequence of YSOs from the rim to the dense core of the cloud, with most of the Class II objects located at the bright rim. The YSOs appear to be aligned along two different directions towards the O6.5V type star HD 206267 and the B0V type star HD 206773. This is consistent with the Radiation Driven Implosion (RDI) model for triggered star formation. Further the apparent speed of sequential star formation is consistent with the speed of propagation of shocks in dense globules as derived from numerical simulations of RDI.

Subject headings: stars: low mass, pre-main-sequence, ISM: clouds and H II regions: individual: SFO 38, IC 1396

1. Introduction

Observational and theoretical studies of star formation over the last decade have increasingly strengthened the idea that massive young stars play an important role in triggering the formation of subsequent generations of stars. The triggers of star formation which are typically in the form of wind and radiation from the massive stars or expansion of H II regions essentially involve the induction of compression of a molecular cloud externally. Among several proposed theories, two models have gathered sufficient observational support in order to be regarded as the most plausible models for triggered star formation. In the first model known as the *Collect and Collapse* (Elmegreen & Lada 1977; Hosokawa & Inutsuka 2006) model, an expanding H II region sweeps up material into a dense bordering layer between the H II region and the molecular cloud. The compressed shell of dust and gas undergoes fragmentation and gravitational collapse to form new stars. Observational evidence supporting the “collect and collapse” model includes detection of a dense, fragmented shell of gas with newly formed stars surrounding the H II region (Deharveng et al. 2003, 2009; Zavagno et al. 2006, 2007). The *collect and collapse* model is however primarily to explain the triggered formation of massive stars. An equally likely model based on *Radiation Driven Implosion (RDI)*, involves the creation of shock front at the surface of molecular clouds due to photoevaporation from the surfaces of molecular clouds exposed to the UV radiation of nearby massive young stellar clusters. The enhanced inward pressure triggers the formation of new protostellar cores or compresses pre-existing ones to form a new generation of stars. Observational evidence for the RDI model includes typical spatial distribution and gradient in evolutionary phases of young stellar objects (Ikeda et al. 2008). There is however considerable ambiguity regarding whether RDI actually induces the gravitational collapse or merely exposes the young stars by photoevaporation, since these two scenarios are observationally indistinguishable. Thus additional tests to ascertain the temporal feasibility of shock waves from nearby OB associations actually triggering sequential star formation are required to strengthen the arguments in favor of RDI.

Bright-rimmed clouds (BRCs) are isolated molecular clouds located on the edges of evolved H II regions, which are found to have many signposts of star formation, i.e., *IRAS* point sources, molecular outflows, HH objects etc. Sugitani et al. (1999) and Sugitani et al. (2000) observed a sample of 89 BRCs and found an excess in the luminosities and luminosity-to-cloud ratios of embedded *IRAS* sources when compared with sources in isolated globules, which is an indication of enhanced star formation in the BRCs. Young stellar objects seemingly aligned along the axis towards the ionizing cluster were detected via near-infrared (NIR) imaging of 44 of these BRCs. There is also evidence for an age gradient, with older stellar objects closer to the OB cluster and the younger objects well inside the globules, aligned with the *IRAS* sources. These results are consistent with sequential formation of stars while the shock front advances further and further into the molecular cloud. Thus BRCs are ideal objects for studying and verifying the different models of triggered star formation.

The H II region IC 1396, powered by the O6.5V type (Stickland 1995) star HD 206267 in the Trumpler 37 cluster, appears to sweep up a molecular ring of radius 12 pc (Patel et al. 1998) and is surrounded by 11 Bright-Rimmed clouds with embedded *IRAS* point sources (Sugitani & Ogura 1994; Sugitani et al. 1991). SFO 38, also known as IC 1396N, is located at a projected distance of ~ 11 pc to the north of HD 206267 with the bright rim corresponding to the ionization front facing the O6.5V star. SFO 38 is located in the Cep OB2 association at a distance of 750 pc (Matthews 1979). More recent *Hipparcos* parallax based measurements estimate the distance to Cep OB2 association to be 615 pc (de Zeeuw et al. 1999). However in order to make our results comparable to most published results, in this paper we adopt a distance of 750 pc for SFO 38. The derived luminosities may therefore be overestimated by more than 40% and physical sizes by 20%. The region is associated with *IRAS* 21391+5802, a very young intermediate-mass object, with a luminosity of $235 L_{\odot}$ (Saraceno et al. 1996), which powers an extended bipolar outflow (Sugitani et al. 1989). Based on millimeter observations Beltrán et al. (2002) resolved *IRAS* 21391+5802 into an intermediate-mass source named BIMA 2 surrounded by two less massive and smaller objects, BIMA 1 and BIMA 3. Valdetaro et al. (2005) detected H_2O maser emission at 2.2 GHz towards SFO 38 which is consistent with an intermediate-mass object. Neri et al. (2007) used still higher angular resolution millimeter interferometric observations to reveal that the intermediate-mass protostar BIMA 2 itself consists of multiple compact sources. The gas emission surrounding *IRAS* 21391+5802 traces different molecular outflows (Codella et al. 2001; Beltrán et al. 2002, 2004). NIR images of the region have also revealed a number of small scale molecular hydrogen and Herbig-Haro (HH) flows (Nisini et al. 2001; Sugitani et al. 2002; Reipurth et al. 2003; Caratti o Garatti et al. 2006; Beltrán et al. 2009). These observations confirm the on going star formation in the dense core of SFO 38.

Getman et al. (2007) identified the mid-infrared (MIR) (*Spitzer*) counterparts of X-ray sources detected in *Chandra* observations and found that the young stellar objects (YSOs) are oriented toward the ionizing star HD 206267 and show an age gradient consistent with the RDI model for triggered star formation. Recently Beltrán et al. (2009) studied the YSO population of SFO 38

by obtaining deep J, H, K' broadband images and deep high-angular resolution observations in the H₂ narrowband filter. Beltrán et al. (2009) did not detect any clear NIR excess close to the rim, which is in contrast to the age 1 Myr of the stellar population concluded by Getman et al. (2007). Beltrán et al. (2009) suggest that the YSOs closer to HD 206267 could actually be younger than the Class II objects they appear to be since their circumstellar environment were disrupted completely by intense UV radiation field from the OB association. Beltrán et al. thus suggest that in general the apparent age sequence seen close to OB associations need not necessarily be the actual evolutionary sequence and in the case of SFO 38 there is no concrete evidence of star formation by the nearby OB association.

In this paper we address the controversial issue of the distribution of YSOs by making use of the extremely sensitive *Spitzer* IRAC (3.6 to 8.0 μm) & MIPS (24 μm) data in order to probe *all* embedded YSOs and protostars in SFO 38. This thus extends the work by Getman et al. (2007), who had considered the 3.6–5.8 μm characteristics only of those MIR sources from which X-ray emission had been detected. Our approach also complements the work by Beltrán et al. (2009) which makes use of only the NIR observations to decipher any age gradient of the YSOs. In this work we shall show that most of the Class 0/I sources identified in the MIR are either barely detected (with large uncertainties in fluxes) or not detected at all in the NIR and in the X-rays. In this paper we have completed the multiwavelength overview of SFO 38 by obtaining optical broadband images in *BVRI* bands and narrow band H α image to understand the detailed structure of the bright-rim. Further in order to confirm the “*youth*” of the YSOs identified in the MIR we have made use of medium resolution spectroscopy of the optically visible YSOs in H α line emission. Observation details of *Spitzer* and optical *BVRI* imaging and medium resolution spectroscopy are presented in § 2. We describe the selection of YSO candidates based on MIR color-color diagram (CCD) and the detailed analysis of optical–MIR data in section § 3. In § 4 we discuss the probable star formation scenarios and in § 5 we summarize the results.

2. Observations and Data Reduction

2.1. *Spitzer* IRAC & MIPS observations

We have extracted IRAC (3.6, 4.5, 5.8, & 8 μm) and MIPS (24 & 70 μm) observations from the *Spitzer* Space Observatory archive (Program ID 30050: Star Formation in Bright Rimmed Clouds by Fazio et al.). The IRAC data were taken in the High Dynamic Range (HDR) mode using a single AOR (Astronomical Observation Request) with a five-point dither pattern. We have processed both the short (0.6 sec) and the long (12 sec) integration Basic Calibrated Data (BCD) frames in each channel using the Artifact mitigation software developed by Sean Carey ¹ and created mosaics using MOPEX. In all IRAC bands we detect point-sources down to 70 μJy . We have also created

¹ http://web.ipac.caltech.edu/staff/carey/irac_artifacts/index.html

mosaics of the MIPS 24 and 70 μm BCDs using MOPEX. Both data sets are of reasonably good quality. The 70 μm -image, due to the lower angular resolution and smaller area mapped, shows only one bright point-like source embedded in the globule.

We have carried out multiframe PSF photometry using the tool APEX developed by Spitzer Science Center(SSC) on all the *Spitzer* IRAC images and on the MIPS images. The long integration 3.6 and 4.5 μm IRAC images show signs of saturation on bright stars. For the saturated sources, the photometry derived from the short integration images were used. It is difficult to disentangle the sources in regions of strong emission from the associated Photon Dominated Regions (PDRs) from the surrounding clouds and to derive their accurate photometry. We have used a combination of automated routines and eye-inspection to detect sources and extract photometry of these sources from the IRAC and MIPS images. For sources, which APEX failed to detect automatically at one or several wavelengths, we have used the user list option in APEX to supply the coordinates for the source to successfully derive a PSF fit. This enabled us to derive photometry for every source which we could visually identify on any image. Following the IRAC and MIPS Data Handbooks we have adopted the zero-points for conversion between flux densities and magnitudes to be 280.9, 179.7, 115.0, 64.1 and 7.14 Jys in the 3.6, 4.5, 5.8, 8.0, and 24 μm bands, respectively.

2.2. Optical *BVRI* Photometry

SFO 38 was observed on 17th July, 23rd August and 15th September 2009 using Bessell’s broad band filters *VR* (300 \times 8 s, 300 \times 8 s), *BVI* (900 \times 8 s, 300 \times 8 s, 150 \times 8 s) and *BI* (900 \times 8 s, 120 \times 12 s) respectively and on 4th November 2008 using the narrow band *H α* (900 s) with the Himalayan Faint Object Spectrograph Camera (HFOSC) mounted on the 2m Himalayan Chandra Telescope (HCT) of the Indian Astronomical Observatory, Hanle, India². HFOSC uses the central 2K \times 2K region of the 2K \times 4K CCD in imaging mode and covers a field of 10’ \times 10’ with a plate scale of 0’296 *pixel*⁻¹. The nights were photometric with an average seeing of 1’’5 to 1’’8. Landolt (1992) photometric standard stars were observed on all the nights to calibrate the target stars. Data were reduced using standard tasks available within Image Reduction and Analysis Facility (IRAF)³. Bias subtracted, flat field corrected and aligned frames were combined to make the master frame for each filter. Astrometric calibration was applied to the master frames using the IDL procedure *STARASTT* of IDL Astronomy User’s Library⁴. Photometric magnitudes were calculated by aperture photometry with the optimal aperture adopted as the radius where the difference in magnitudes between two consecutive apertures is less than 1%. The limiting magnitude is defined as the magnitude at which the mean magnitude error of the star becomes 0.1 mag which implies a 10 σ detection corresponds

² <http://www.iiap.res.in/centers/iao>

³The IRAF software is distributed by the National Optical Astronomy Observatory under contact with National Science Foundation. <http://iraf.noao.edu/>

⁴ <http://idlastro.gsfc.nasa.gov/>

to a signal-to-noise ratio (S/N) of 10. The limiting magnitudes were V: 21, R: 21 on 17th July , B: 22, V: 22, I: 19.5 on 23rd August and B: 22.2, I: 20.2 on 15th September. Aperture corrections for each frame were derived from the bright and isolated stars and applied to the faint stars. The standard deviation of residuals of observed and transformed magnitudes and colors of the standard stars are within the range of 0.01-0.02 mag. We used the broadband R filter image for continuum subtraction from the narrow band $H\alpha$ image of SFO 38. Based on the recipe of Waller (1990), the point spread functions of the R-band and the narrow band $H\alpha$ images were matched and the images were scaled before subtraction to get the $H\alpha$ emission line image of SFO 38.

2.3. Medium Resolution Spectroscopy

Medium resolution ($\sim 7 \text{ \AA}$) spectra were obtained for relatively bright and optically visible YSOs during July–November of both 2008 and 2009 in the wavelength range (5200–9200 \AA) with the Himalayan Faint Object Spectrograph Camera (HFOSC) mounted on the Himalayan Chandra Telescope (HCT). Typical exposure time of each spectrum was 3600 s. The spectra were bias subtracted, flat fielded and the one-dimensional spectra were extracted using the standard tasks of Image Reduction and Analysis Facility (IRAF). The arc lamp spectra of FeNe were used for wavelength calibration. We further used the strong night sky emission lines e.g. [OI] $\lambda 5577 \text{ \AA}$, $\lambda 6300 \text{ \AA}$ lines and rotational and vibrational bands of OH in the red region of the individual target spectrum to improve the wavelength calibration and achieved an accuracy of $\pm 0.5 \text{ \AA}$ for each target star.

3. Results and Analysis

3.1. Mid-Infrared (3.6 to 24 μm) view of SFO 38

Figure 1 presents the three-color image of SFO 38 using the IRAC 3.6, 8.0 and the MIPS 24 μm bands. The image shows that the emission from the front side of the globule is dominated by strong polycyclic aromatic hydrocarbon emission (PAH-emission), and rather clumpy. This could in part be due to Rayleigh-Taylor instabilities at the ionization front, but it is also due to the outflows from the young stars. The cometary shape of the globule is quite apparent with the tip pointed towards the O star HD 206267 and the eastern edge appears to be more abruptly truncated to the south. This indicates that the south-eastern edge of the globule has most likely experienced intense ionizing radiation field, which has eroded the cloud material more than on the western side. Comparison with the $H\alpha$ emission line image (Fig. 2) also confirms the presence of a more pronounced ionization front to the south-east and a rather tenuous layer of ionized gas to the west of SFO 38.

The aim of this paper is to identify the young and embedded stellar population in SFO 38. While the 3.6 and 4.5 μm IRAC data is particularly sensitive, a large number of stellar objects in

addition to the YSOs also detected in these bands. We have thus used all sources detected either at 5.8 or at 8.0 μm or at both wavelengths to create a list of MIR sources in SFO 38. Photometry for all these sources, if detected, are then extracted from the 3.6 & 4.5 μm images. We thus detect 98, 106, 106 and 98 sources respectively in the IRAC 3.6, 4.5, 5.8 and 8.0 μm images and 14 and 1 sources respectively in the MIPS 24 & 70 μm images. All the sources detected at 24 μm are found to have been detected in the IRAC bands. In all we identify a total of 110 MIR sources. We have crosscorrelated the MIR sources with the NIR sources in our mapped region from the 2MASS point source catalogue, as well as the sources detected in the NIR by Nisini et al. (2001) and Beltrán et al. (2009). We have used the following association radii : 1'' for the IRAC images, 2''.5 for the MIPS 24 μm image and 2'' for NIR data. Table 1 gives the coordinates of the 110 sources identified in SFO 38 together with their NIR magnitudes, *Spitzer* IRAC and MIPS flux densities and a preliminary classification based on selected color-color plots and other criteria described in Sec. 3.2. In Table 1 we have used the prefix SFO38, but throughout the paper we refer to them as MIR-*nn*, where *nn* is the number of the source. Out of the 110 sources 80 were found to have NIR counterparts. However 10 sources out of the 80 sources with NIR counterparts were found to coincide with the H₂ knots identified by Beltrán et al. (2009).

Additionally in order to identify the stellar and pre main sequence (PMS) stars we used photometry extracted from the IRAC 3.6 and 4.5 μm long integration images. The 3.6 and 4.5 μm images are more sensitive, have a cleaner PSF, and appear to be less affected by nebular emission than the 8 μm image. We identified 161 additional sources, which are detected in both the 3.6 and 4.5 μm wavebands. Of these sources 113 are found to have NIR counterparts, and 6 sources are coincident with H₂ emission knots.

3.2. Classification of YSOs based on Near- and Mid-infrared colors

In regions of high obscuration like SFO 38, which has a visual extinction of up to 20 mag, mid-infrared color indices provide an ideal tool for identifying YSOs and classify them according to their phases of PMS evolution (Getman et al. 2007). Here we use several color indices generated using the *Spitzer* IRAC and MIPS data to characterize the evolutionary stages of the MIR sources detected in SFO 38.

Stern et al. (2005) demonstrated that (a) normal star-forming galaxies and narrow-line AGNs with increasing 5.8 and 8.0 μm and (b) broad-line AGNs with red, nonstellar SEDs, result in colors which are very similar to bona-fide YSOs. Thus prior to identifying PMS sources based on the color indices it is necessary to inspect deep IRAC images for contamination due to the extragalactic sources. Gutermuth et al. (2009) have extensively discussed the criteria for identifying such extragalactic objects in the IRAC color-color diagrams. Using the criteria given in the appendix of their paper, we identify MIR-2, 17, 68, 70, 75, 81, 84, 89, 101 and 103 as AGNs and MIR-77, 81, 93 and 103 as galaxies strongly emitting in the PAH bands. Of these sources, MIR-17, 89 and 103 satisfy most of the criteria for extragalactic objects. The profiles of sources in the *R*-band is typically

quite a good indicator of whether the source is actually extragalactic or stellar. However all the sources in SFO 38 which satisfy the criteria mentioned above are extremely faint so that with the exception of MIR-2, these sources though visible are not detected clearly enough in the R -band so that the intensity profile can be studied. Further, none of the sources is detected in the MIPS 24 μm image either. The R -band profile of MIR-2 appears to be stellar with a faint companion on one side and MIR-84 is associated with an $\text{H}\alpha$ emission star, so we do not identify both these sources as extragalactic. In the absence of any conclusive evidence we presently assume the sources identified by the empirical criteria as above to be extragalactic.

The 4.5 μm IRAC band of *Spitzer* covers many of the H_2 pure rotational lines, as a result of which this band records a large excess of emission at the position of the unresolved blobs of shocked emission from high velocity outflows which interact with the molecular cloud. Using the empirical criteria outlined by Gutermuth et al. (2009) here we flag the sources MIR-24, 27, 53, 65 and 98 as possible features due to shocked H_2 emission. Based on 2.12 μm H_2 integrated line emission Beltrán et al. (2009) identified as many as 97 emission features possibly created by H_2 excitation by shocks driven by outflows powered by YSOs. We find that 10 out of the 110 MIR sources that we have identified are associated with such H_2 knots. These include the sources MIR-20, 24, 27, 35, 53, 65, 74, 75, 98 and 105. Thus the color indices for 5 out of the 10 sources are consistent with the observed association with H_2 knots. The source MIR-75 which also satisfied the criteria for being an extragalactic object is thus identified as a H_2 knot.

Figure 3 presents color-color diagrams of NIR, IRAC and MIPS 24 μm sources detected in the SFO 38 globule. We have used several criteria (shown as dashed lines and boxes in Figure 3) to identify the potential YSOs using these color-color diagrams.

The most stringent classification scheme uses the IRAC ([3.6]–[5.8]) colors and the [8]–[24] IRAC and MIPS color. At 24 μm the reddening due to extinction is small and the photospheric colors are very close to zero for all spectral types (Muzerolle et al. 2004). Therefore the [8]–[24] color is very sensitive to infrared excess, but of course not all young stars are bright enough to be detected at 24 μm . Using this color-color diagram we find fourteen sources with infrared excess (Figure 3 (*left*)). We identify MIR-34, 36, 48, 50, 54, 55 and 59 as Class 0/I sources, while MIR-11, 31, 38, 45, 82 and 86 are within the Class II regime and MIR-29 which has a large [8.0]–[24] color excess and very small value for the [3.6]–[5.8] color is identified as a transition disk object. Jørgensen et al. (2007) predicted sources with [3.6]–[4.5] > 1.0 and [8]–[24] > 4.5 to be YSOs driving molecular outflows. We find that the sources MIR-34, 48, 50, 54, and 59, all of which have been identified as Class 0/I objects also satisfy the criteria for being sources driving outflows.

Figure 3 (*middle*) presents the [3.6]–[4.5] vs [5.8]–[8.0] color-color plot for the sources detected in all the IRAC bands. Sources with the colors of stellar photospheres are centered at ([3.6]–[4.5],[5.8]–[8.0])=(0,0) and include foreground and background stars as well as diskless (Class III) pre-main sequence stars. Sources which satisfy the criteria $-0.1 \leq [3.6]–[4.5] \leq 0.1$ and $0.2 \leq [5.8]–[8.0] \leq 1.1$ are classified as the transitional disk objects (Fang et al. 2009) which also do not have

any NIR color excess. The box outlined in Figure 3 (*middle*), defines the location of Class II objects (Megeath et al. 2004; Allen et al. 2004), i.e. sources whose colors can be explained by young, low-mass stars surrounded by disks. Hartmann et al. (2005) have shown from their observations of young stars in the Taurus-Auriga complex that Class 0/I protostars require $[3.6]-[4.5] > 0.7$ and $[5.8]-[8.0] > 0.7$. With the exception of MIR-29, the classes derived for the sources identified in the MIPS 24 μm band and plotted in Fig. 3(*left*) are completely consistent with the classes derived from the $[3.6]-[4.5]$ vs $[5.8]-[8.0]$ color-color plot. We identify 10 of the MIR sources as being associated with H₂ knots, this includes MIR-75, which otherwise satisfies the criteria for extragalactic objects. We also plot NIR and *Spitzer* MIR color-color diagram of the identified YSOs and transitional Disk objects in Figure 3 (*right*).

Table 1 presents a summary of classification of the MIR sources based on the color-color diagrams presented here. We have additionally looked into the $[3.6]-[5.8]$ vs $[4.5]-[8.0]$ color-color diagram and found that the Classes derived from this diagram are consistent with the classes derived based on the color-color diagrams presented here. For most sources it was possible to arrive at a unique Class based on all three color-color diagrams. For all sources the Class derived based on at least two color-color diagrams match.

Use of the more sensitive long integration 3.6 and 4.5 μm images in combination with 2MASS data (following a classification scheme involving the $K_s-[3.6]$ and $[3.6]-[4.5]$ colors) yields an additional 113 sources, 11 of which are PMS objects. Since the long integration 3.6 and 4.5 μm images go deeper and are less affected by extinction than the 2MASS survey, we also checked how many of these IRAC sources which have no 2MASS associations are likely to be PMS stars. Among the 48 remaining sources which have no NIR counterparts, following the arguments of Mookerjee et al. (2009) if we use the color criterion, $[3.6]-[4.5] \geq 0.2$, we obtain 8 sources. However 6 of these 8 sources are actually associated with H₂ emission knots as detected by Beltrán et al. (2009). Table 2 lists the 13 PMS candidates identified on the basis of NIR and 3.6 and 4.5 μm magnitudes.

Excluding the H₂ knots and the possible extragalactic objects we identify 10 Class 0/I sources, 3 Class I sources, 13 Class I/II sources (occupying the top-left and bottom-right corners), 14 Class II sources and 19 transitional disk objects in SFO 38. Thus we find a total of 40 YSOs (Classes 0/I/II) and 13 PMS candidates based on MIR color indices. We note that 13 Class I/II objects and 19 Transitional Disk objects are $\sim 30\%$ of the selected YSOs and show noticeable color excess only beyond 6 μm .

3.3. H α emission of SFO 38 and spatial distribution of YSOs

Sugitani et al. (1991) classified SFO 38 as a *B* type BRC powered by O6.5 star HD 206267. The bright rim structure is quite prominent in the continuum subtracted H α line image of SFO 38 in Figure 2. The H α emission nebulosity of the bright-rim of the globule is asymmetric with respect to the geometric axis of the globule as well as the direction of the adopted ionizing source

HD 206267. The ionized rim appears to be brighter towards the east and rather diffuse towards the western edge, facing HD 206267. The $H\alpha$ intensity distribution of the diffuse material in between the bright-rim and the ionizing star also show similar kind of asymmetric distribution as that of the bright-rim. We, therefore, searched for other massive O and B type stars in the surrounding region that can produce the relatively brighter $H\alpha$ emission on the left side of the globule. We find a B0V type (Jaschek & Egret 1982) star HD 206773 which is situated on the symmetry axis of the left side of the bright-rim at a projected distance of ~ 7.6 pc from SFO 38. de Zeeuw et al. (1999) tagged HD 206773 as a member of Cep OB2 association. The distance towards the star is between 550–1000 pc, adopting the parallax measurement and the associated error (van Leeuwen 2007) which is consistent with the distance of SFO 38. The number of ionizing photons emitted per second by a B0V star is $\sim 10^{48.02}$ (Sternberg et al. 2003) and using $n_H \simeq 10^7 \text{ m}^{-3}$ for number density of hydrogen in the interior of the H II region IC 1396, the Strömgren radius would be ~ 8.5 pc which suggests that HD 206773 could be a potential ionizing source for SFO 38. Fig. 2 shows the distribution of the YSOs and the directions toward HD 206267 and HD 206773 on the $H\alpha$ line image. We find that most of $H\alpha$ emitting Class II objects lie within the bright-rim. Class I/II objects are situated behind the Class II objects in the intermediate region between the bright-rim and the dense portion of the globule. All the Class 0/I and Class I objects are situated well within the dense core part of the globule. There is no Class 0/I to Class I/II YSO which is situated before the ionized rim. The YSOs appear to have elongated distribution to the right and left sides of the bright rim with two different axes of elongation.

3.4. Additional YSO candidates based on $H\alpha$ emission

$H\alpha$ emission surveys are very useful to identify low mass ($< 2 M_\odot$) Classical T Tauri stars (CTTS) in young star forming regions as the $H\alpha$ emission is due to the accretion of circumstellar material in YSOs. These observations also detect a fraction of Weak-lined T Tauri stars with weak $H\alpha$ emission which is believed to arise from enhanced chromospheric activities. Based on $H\alpha$ emission, we searched for the additional YSO candidates available in the literature outside the field of view of *Spitzer* observations to complement the list of YSOs around SFO 38. Many of the candidate YSOs in and around SFO 38 were found during $H\alpha$ objective prism survey by Ogura et al. (2002); Ikeda et al. (2008). A total of 14 out of the 17 $H\alpha$ emission line sources (Ogura et al. 2002; Ikeda et al. 2008) are situated within the field of view of IRAC. We consider the rest of the $H\alpha$ emission line sources *viz.*, [OSP2002] BRC 38 1, [OSP2002] BRC 38 16, and [OSP2002] BRC 38 17 as YSO candidates. We also find 4 $H\alpha$ emission line sources near SFO 38 in the catalogue of point-source $H\alpha$ emission-line objects selected from the INT/WFC Photometric $H\alpha$ Survey (IPHAS) of the northern Galactic plane (Witham et al. 2008). We identify IPHAS J214027.32+581421.3 as [OSP2002] BRC 38 2, IPHAS J214036.90+581437.9 as [OSP2002] BRC 38 6, IPHAS J214041.23+581158.5 as [GFG2007] 64. Thus, we also consider [GFG2007] 64 and IPHAS J214042.81+581937.4 as YSO candidates.

3.5. Optical and NIR variability

Out of the 115 sources (110 MIR + 5 H α emission sources) mentioned in Secs. 3.2, 3.4 and 3.6 we detect a total of 39 sources in *B*, 46 sources in *V*, 51 source in *R* and 63 source in *I* bands. The *BVRI* magnitudes of all the sources detected in *V* band are presented in Table 3. We do not detect the optical counterparts of the 13 PMS candidates listed in Table 2. Photometric variability, a very common characteristic of YSOs, can happen due to various physical processes *viz.*, variation in stellar spots or variable obscuration which affect the emission from its photosphere. Since we have *BVI* observations separated by several months, we have also looked for the variability in the *BVI* bands for all the sources. The median variability in *BVI* bands are ~ 0.04 mag which is also indicative of the accuracy of the optical photometric measurements. We consider a source to be *variable* if the magnitude difference is ≥ 0.1 mag (Table 3) at the two observing epochs. MIR-5, MIR-32, MIR-43, MIR-45 and MIR-49 show variation in *BVI* bands. In particular MIR-5 with $W_\lambda(\text{H}\alpha) \sim 80 \text{ \AA}$ shows ~ 1 mag variability in *B* over a timescale of month.

YSOs also show variation in NIR bands which may or may not have any correlation with the optical variation (Eiroa et al. 2002). Both the stellar photosphere and the circumstellar disk contribute to the NIR fluxes of PMS stars. Hence, NIR variability can be either due to the same physical processes responsible for optical variability or any structural variability of disk and circumstellar materials. We compare the NIR magnitudes from 2MASS (Cutri et al. 2003) and from the more recently obtained JHK magnitudes by Beltrán et al. (2009) of the sources reported in both the datasets to identify NIR variability. Sources which have shown variation of ~ 0.1 mag in any of the NIR band are listed in the last column of Table 1.

3.6. Medium resolution spectra of YSOs

The H α emission though a very prominent feature in the spectrum of the YSO is not sufficient to identify YSOs because there also exist other kinds of H α emission line stars *viz.*, *Be*, *Mira* stars etc. Medium resolution spectroscopy is helpful to distinguish the YSOs from the *Be* and *Mira* stars. Figure 4 presents sample spectra observed with HFOSC of a few YSOs. The prominent features e.g. H α , CaII NIR triplet etc. are marked in the respective spectra. We have detected strong H α emission in most of the Class II objects except BRC 38 16 and therefore we do not consider it as a YSO in the remainder of the paper. Log of spectroscopic observations and H α equivalent widths (W_λ) of the individual YSOs are given in Table 4. BRC 38 6 (MIR-31) is the brightest Class II object detected in optical band. From the multiepoch spectroscopic observations we find that MIR-31 shows variable H α emission (Table 4). We have also detected OI $\lambda 7773$ (blend of OI $\lambda 7771.96$, $\lambda 7774.18$, $\lambda 7775.40$), OI $\lambda 8446$ (blended with Pa18 $\lambda 8437$) CaII infrared triplet i.e $\lambda 8498$ (blended with Pa16 $\lambda 8502$), $\lambda 8542$ (blended with Pa15 $\lambda 8545$) and $\lambda 8662$ (blended with Pa13 $\lambda 8665$) and several other Paschen lines e.g. Pa10 $\lambda 9014$, Pa11 $\lambda 8862$, Pa12 $\lambda 8750$, Pa14 $\lambda 8598$, Pa17 $\lambda 8467$, Pa19 $\lambda 8413$, Pa20 $\lambda 8392$ in MIR-31. According to Muzerolle et al. (1998b), OI $\lambda 7773$

is a very sensitive indicator of infall in the context of magnetospheric accretion scenario. LiII $\lambda 6708$ ($W_\lambda \sim 0.7 \text{ \AA}$) is also present in the spectra of MIR-31. All these spectroscopic features indicate that MIR-31 is indeed a YSO which is going through an active accretion phase. We have detected [OI] $\lambda 6300$ and [OI] $\lambda 6363$ and [SII] $\lambda 6717$ and [SII] $\lambda 6731$ emission lines in MIR-45 which are well known signatures of outflows from YSOs. We also find a positive correlation between $H\alpha$ emission and MIR excess for YSOs with $W_\lambda(H\alpha) \leq 40 \text{ \AA}$. We have detected sporadic $H\alpha$ emission in transitional disk object MIR-29 on 3rd November 2008. We observed the object in 2009 also but we do not find any further $H\alpha$ emission. We have detected weak $H\alpha$ emission from two more transitional disk objects e.g. MIR-43 ([GFG2007] 62) and MIR-76 ([GFG2007] 81). We also obtained the spectra of few more transitional disk objects e.g. MIR-1, MIR-2, MIR-9, MIR-18 and MIR-108 and do not find $H\alpha$ emission in any of these objects.

3.7. Spectral Classification

We have classified the observed optical spectra by manual inspection of the spectra of target stars and also by comparing it with the spectra of known spectral type. We observed several stars with spectral type of F to M from Jacoby et al. (1984), Valdes et al. (2004) and Kirkpatrick et al. (1991) with HFOSC using the same set up as the target stars to minimize the effect of instrumental signatures and resolution. From preliminary analysis we find that the YSOs are of spectral type K and M.

For more accurate classification in the range of spectral type K–M, we use the calibration file provided in the *SPTCLASS* (Hernández et al. 2004) code for various absorption features *viz.*, Tio bands etc. The detailed information of the classification scheme can be found in the *SPTCLASS* code⁵. This scheme measures the equivalent widths or “indices” of the absorption features which are sensitive to T_{eff} using the adjacent blue and red continuum bands and calibrate the indices against the spectral type of the stars. Spectral type of the target star is determined from the weighted mean of the spectral types obtained from different absorption features of the target star excluding the apparently anomalous values. As this classification scheme uses the local continuum of the absorption feature, it is insensitive to reddening and the S/N ratio. Further, the spectral features which are used for classification are also insensitive to the luminosity class. The errors in the spectral type determination come from the measurement of indices and the standard deviation of the spectral types obtained from different absorption features. To check the applicability of the adopted calibration on *HFOSC* spectra we classify the *HFOSC* spectra of a few K and M type stars and retrieve the spectral type within ~ 0.5 subtype. We then use the same calibration scheme to classify the YSO spectra. We further explore the Fe I $\lambda 6495 \text{ \AA}$ line to classify the spectra of early K type stars (Gray & Corbally 2009). The “index” or equivalent width of $\lambda 6495$ line was calculated for spectral types F–K, using the *HFOSC* spectra of stars with known spectral

⁵<http://www.astro.lsa.umich.edu/~hernandj/SPTclass/sptclass.html>

type taken from Jacoby et al. (1984); Valdes et al. (2004). The results of our classification are summarized in Table 4. We also tabulate the effective temperatures of YSOs using the table of Kenyon & Hartmann (1995). Using the $V-I$ color of a particular spectral type and our optical $BVRI$ observations we calculated the A_v assuming the normal interstellar extinction law as given by Bessell & Brett (1988). The average extinction towards the globule is estimated to be $A_v = 2.5$ mag.

3.8. Rate of accretion from $H\alpha$ emission

The $H\alpha$ emission along with the other Balmer lines, have always been the iconic spectral diagnostics of accretion of circumstellar materials in the YSOs. Magnetospheric accretion models have provided satisfactory explanation of the observed spectral characteristics of accretion Classical T Tauri Stars (CTTS) e.g. broad asymmetric line profiles etc. (Muzerolle et al. 1998a, 2001). According to the magnetospheric accretion model the stellar magnetic field disrupts the circumstellar disk at several stellar radii and accreting material fall to the stellar surface along the magnetic field lines (Koenigl 1991). Magnetospheric accretion models suggest that the hydrogen emission lines form in the infall zone, so that the blue shifted asymmetric emission line profiles arise due to partial obscuration of the flow by the inner part of the accretion disc and the red shifted absorption profiles result from infalling material at near free-fall velocities on the stellar surface (Muzerolle et al. 1998a). Strength of the $H\alpha$ emission line has been widely used to distinguish the actively accreting CTTS from their less active and evolved counterparts i.e Weak-lined T Tauri Stars (WTTS). White & Basri (2003) proposed to classify a YSO as CTTS if $W_\lambda(H\alpha) \geq 3 \text{ \AA}$ for K0–K5 stars, $W_\lambda(H\alpha) \geq 10 \text{ \AA}$ for K7–M2.5 stars, $W_\lambda(H\alpha) \geq 20 \text{ \AA}$ for M3–M5.5 stars, and $W_\lambda(H\alpha) \geq 40 \text{ \AA}$ for M6–M7.5 stars. They also proposed that the stars with full width of $H\alpha$ emission line at 10 % of the peak intensity ($H\alpha[10\%]$) greater than 270 km s^{-1} are accreting CTTS independent of spectral type. We identify 9 stars as CTTS and 5 stars as WTTS according to the above mentioned criteria (Table 4). Natta et al. (2004) showed that $H\alpha[10\%] \geq 200 \text{ km s}^{-1}$ can be used to distinguish the accretors and non accretors as well as to derive an approximate estimate of the accretion rate \dot{M}_{ac} quantitatively by the following relation, $\log \dot{M}_{ac} = -12.89 (\pm 0.3) + 9.7 (\pm 0.7) \times 10^{-3} H\alpha[10\%]$ where $H\alpha[10\%]$ is in km s^{-1} and \dot{M}_{ac} is in $M_\odot \text{ yr}^{-1}$. In order to estimate the accretion rates for some of the well resolved $H\alpha$ line profile we fitted Gaussian profiles to the $H\alpha$ emission lines and calculate the equivalent width and FWHM of each line profile. The measured FWHM of each profile has been deconvolved assuming a Gaussian instrumental profile. We calculate the $H\alpha[10\%]$ for these objects and transformed them into velocity units. We did not correct for the underlying photospheric absorption in $H\alpha$ if there is any. Table 4 presents the accretion rates \dot{M}_{ac} , calculated using the above formula along with the measured values of $H\alpha[10\%]$. Based on the observed multiepoch spectra we find variable accretion rates in BRC 38 1, MIR-5, MIR-31, MIR-32 and MIR-45.

3.9. Optical Color-Magnitude Diagram

Figure 5 presents the extinction corrected V vs. V-I diagram of the YSOs near SFO 38. We have corrected for the extinction of individual objects with known spectral types and used an average value of $A_v=2.5$ mag when the spectral type is not known. In order to estimate the mass and age of the YSOs we overplot the isochrones from Siess et al. (2000) assuming a distance of 750 pc Matthews (1979). We find that most of the YSOs (Class II with(out) $H\alpha$) have ages between 1-5 Myr and masses in the range 0.3-2.2 M_\odot . We note that several transitional disk objects are located to the left of the ZAMS line. A closer examination of the position of the transitional disk objects in the MIR color-color diagram (Fig. 3) reveals that 6 out of 7 transitional disk objects which are situated to the left of ZAMS line have $[5.8]-[8]$ color excess < 0.5 and 4 out of 5 transitional disk objects which are situated to the right of ZAMS line have $[5.8]-[8]$ color excess > 0.5 . The transitional disk objects to the left of the ZAMS line are more like Class III objects with smaller values of color excess. We have used an average $A_v=2.5$ mag for extinction correction for these objects because the spectral types are not known. There are several factors that could lead the transitional disk objects to the anomalous position in Fig. 5 e.g. extinction correction, uncertainties in distance and PMS evolution model used. An extinction correction with a smaller A_v (≤ 1 mag) brings all the transitional disk objects closer to, or to the right of the ZAMS line. The distance of IC 1396 is in the range of 615 pc (de Zeeuw et al. 1999) to 900 pc (Contreras et al. 2002) and we adopt a distance of 750 pc for SFO 38 to make our results comparable to most published results. This uncertainty in the distance corresponds to an uncertainty of ± 0.4 mag in the absolute magnitude. Adoption of a distance of 900 pc brings up the transitional disk objects somewhat closer to the ZAMS line but these objects still occupy positions below the ZAMS line. While different theoretical models differ in the details of the PMS evolution, close to the ZAMS line all these models agree with each other and with the empirical ZAMS of the young star clusters. Therefore, the anomalous positions of the transitional disk objects with respect to the ZAMS track in Fig. 5 is primarily due to overcorrection of the extinction. Estimation of mass and age from the color-magnitude diagram (CMD) is strongly dependent on the adopted model (Hillenbrand et al. 2008). The ages can differ by as much as 10 Myr or more when two different models are used on the same dataset (Ikeda et al. 2008). The main source of error in the V vs. V-I diagram is the estimation of extinction towards the globule. In the last column of Table 4 we list the ratios of $E(V-I)/E(B-V)$ which are different from the standard value of 1.6 and indicate that normal extinction law may not hold good for star forming regions due to plenty of patchy obscuring materials. Although the NIR JHK bands suffer comparatively less extinction than the optical $BVRI$ band but for the YSOs, thermal emission also contributes to JHK bands resulting in excess fluxes compared to the main sequence counterparts without disk. For a given model we consider the derived values of the masses and ages as representative values and the age spread of YSOs as more reliable estimate.

3.10. SED of YSOs with MIPS 24 μm detection

In order to interpret the observed SEDs for the YSOs detected at 24 μm and better characterize these sources we have explored the archive of two-dimensional (2D) axisymmetric radiative transfer models of protostars calculated for a large range of protostellar masses, accretion rates, disk masses and disk orientations created by Robitaille et al. (2007). This archive also provides a linear regression tool which can select all model SEDs that fit the observed SED better than a specified χ^2 . Each SED is characterized by a set of model parameters, such as stellar mass, temperature, and age, envelope accretion rate, disk mass, and envelope inner radius. We have used this online tool to generate models, which fit the observed SEDs for the 14 YSOs which have been detected at 24 μm . We restricted the SED fitting tool to explore only distances between 650 and 850 pc. Below we present and briefly discuss the best fit models.

Figure 6 shows results of detailed modeling of the observed SED in the mid-infrared (and sub-mm for MIR-50) for all the YSOs which were detected at 24 μm . A major criticism against the use of these models has been the non-uniqueness of the solutions obtained from the model library. However we find that for all sources the best fit models are distinctively better than the next few models in reproducing all the observed flux densities. Table 5 presents the parameters corresponding to the best fit models for the fourteen sources which we fitted with the accretion disk models.

Robitaille et al. (2006) presented a classification scheme which is essentially analogous to the Class scheme, but refers to the actual evolutionary stage of the object based on its physical properties like disk mass and envelope accretion rates rather than the slope of its near/mid-IR SED. According to the Robitaille et al. classification scheme, MIR-50 and MIR-54, are stage 0/I objects, while all the others are stage II objects. However, the YSOs MIR-34, 36, 48, 55 and 59 were identified as Class 0/I objects based on the color-color diagrams. Next we consider the fact that except for MIR-34 all the sources have rather high visual extinction ($A_v > 40$) and the MIR color-color diagrams we had used to classify the YSOs did not correct for the reddening. Using standard interstellar extinction laws (Indebetouw et al. 2005) and the A_v derived from the models, we find that when de-reddened, the sources MIR-48, 55 and 59 occupy the region typically occupied by Class II objects. However for MIR-34 and 36 the difference in the inferred evolutionary stage can not be explained only in terms of reddening.

Based on the results of fitting the observed SEDs with axially symmetric accretion models we find that all the YSOs analyzed here have low to intermediate-mass central stars. Figure 2 shows that consistent with our expectations the sources located within the globule have $A_v > 20$ mag, while the sources lying at the periphery of the bright rim have A_v between 3–5 mag. In Sec. 3.11 we discuss the two most luminous Class 0/I sources MIR-50 and MIR-54 in detail.

The ages estimated for these fourteen YSOs from the SED models and the location of these sources in BRC 38 show that most of the sources closer to the bright rim have ages between 5–8 Myr. The sources within the BRC and lying almost along the axis of the BRC have ages between

0.1–1 Myr, with the protostellar cluster at the position of IRAS 21391+5802 being the youngest with an age of ~ 0.1 Myr. The age spread estimated for the YSOs (mostly Class II and above) from optical CMD diagram is of the range 1–8 Myr. However, the ages estimated from both methods are higher than the ages obtained from the NIR CMD by Getman et al. (2007).

3.11. The protostellar cluster at IRAS 21391+5802

Interferometric millimeter continuum images have shown that the most luminous source IRAS 21391+5802 in the IC 1396 region can be resolved into three components, named as BIMA 1, BIMA 2 and BIMA 3 (Beltrán et al. 2002). Radio continuum images at 3.6 cm observed with VLA have also identified three peaks VLA 1–3, coincident with the millimeter continuum peaks (Beltrán et al. 2002). Of these three sources VLA 3 is the strongest emitter of radio continuum. Recent sub-arcsecond resolution millimeter observations have identified three components within BIMA 2 itself Neri et al. (2007). The SCUBA images at 450 and 850 μm do not resolve the components of continuum emission associated with IRAS 21391+5802 (Morgan et al. 2008).

We identify MIR-50 and 54 as the mid-infrared counterparts of BIMA 2 and BIMA 3 and do not detect any source associated with BIMA 1. The source MIR-36 is located $3''.8$ away from BIMA 1 and hence is most likely not associated with BIMA 1. We have used the continuum fluxes available in literature to construct the observed SEDs for MIR-50 and MIR-54. In order to make a realistic estimate of the flux densities at 450 and 850 μm from each of BIMA 2 and BIMA 3, we have split up the observed total flux densities at these wavelengths according to the ratio of flux densities of these sources measured at 1.2 mm by Beltrán et al. (2002). Fitting of the observed flux densities with the axially symmetric accretion-based models (Robitaille et al. 2007) shows that MIR-50 (BIMA 2) is a protostellar object with $L = 197 L_{\odot}$ and a mass of $5.97 M_{\odot}$. Both mass and luminosity values match reasonably well with the literature. We note however that the model fitted does not reproduce the interferometric flux densities at 1.2 and 3.1 mm well. This is consistent with the conclusions of Beltrán et al. (2002) that the interferometric observations miss a significant amount of emission. The best fit model for MIR-54 corresponds to a mass of $1.5 M_{\odot}$ and a luminosity of $33.4 L_{\odot}$. Codella et al. (2001) had estimated an integrated luminosity of $233 L_{\odot}$ including both BIMA 2 and BIMA 3 and here we derive a total luminosity of $230 L_{\odot}$. Based on the SED fitting performed in this paper, MIR-54 or BIMA 3 is a low mass Class 0/I protostar and MIR-50 or BIMA 2 is a Class 0/I intermediate-mass star, although Neri et al. (2007) have already shown BIMA 2 as having three components. The SED models derive the age of both these sources to be $\sim 10^5$ yr.

4. Discussion: RDI mechanism at work in SFO 38

Based on the observational evidences in the form of YSOs, an outflow-driving IRAS source and several HH objects, SFO 38 is unambiguously an active star forming region. There is however considerable disagreement regarding whether the star formation is triggered or influenced by the nearby OB association. The two most recent studies of SFO 38 based on Chandra X-ray and *Spitzer* Mid-IR observations (up to $5.8 \mu\text{m}$ Getman et al. 2007) and deep NIR observations (Beltrán et al. 2009) arrive at diametrically opposite conclusions. Considering the spatial and temporal distribution of the fewer YSOs selected by using MID-IR color-color diagram ($[3.6]-[4.5]$ vs. $[4.5]-[5.8]$), Getman et al. (2007) argued in favor of triggered star formation by Radiation Driven Implosion (RDI) model. However Beltrán et al. (2009) did not find either (a) enhanced star formation activity towards the southern rim of SFO 38 or (b) systematic gradient in the evolutionary stage of the YSOs using the deep NIR imaging. Based on the absence of NIR excess from the YSOs Beltrán et al. (2009) concluded that the sources closer to the O type star appear to be more evolved primarily due to the modification of their environment by the intense UV field. Thus, according to Beltrán et al. the evolutionary sequence observed by Getman et al. should not necessarily be interpreted as due to triggered star formation. However Beltrán et al. also concede that NIR-only studies are inadequate to identify all the YSOs in the region.

We explore two possible scenarios which could have been the dominant driving mechanism to initiate the formation of stars in SFO 38 *viz.*, coeval star formation throughout the H II region and triggered star formation by the RDI mechanism. The assumption that the stars near the globule were formed simultaneously with the other stars of the OB association suggests that the distribution of YSOs should be correlated with the distribution pattern of the other massive to low mass stars of the OB association. The observed elongated distribution of YSOs along two different axes in SFO 38 is quite different from the distribution of the known members of Cep OB2 association (Fig. 22 of de Zeeuw et al. 1999). Moreover the ages of the outflow driving IRAS source and the associated protostellar cluster are significantly less than the dynamical age of 3 Myr (Patel et al. 1995) of the H II region created by the massive OB type stars. We thus rule out the possibility of coeval star formation in SFO 38 with the members of Cep OB2 association, although some of the H α emitting sources could have been formed prior to the arrival of the shock front. Next, we investigate the other possibility, based on the RDI model, by comparing our observations with the predicted signatures of the model. The RDI model suggests enhancement of density along the axis of the UV irradiated globule and an age sequence of YSOs with the oldest YSO lying closer to the OB association.

Sequential star formation is considered to be one of the key signatures of triggered star formation via RDI. Beltrán et al. (2009) have cautioned against the use of the spatial distribution of YSOs as a proof of triggered star formation, by arguing that intense UV fields close enough to the OB associations tend to destroy the protoplanetary disks around the YSOs and thus make them appear to be older. However we find this argument untenable for the case of SFO 38, since the typical radius of influence of O stars is found to be $< 1 \text{ pc}$ (Balog et al. 2007; Hernández et al.

2008; Mercer et al. 2009), while the mean projected distance of the nearest O and B -type stars close to SFO 38 is ~ 9 pc. Thus the spatial distribution of the YSOs discussed in SFO 38 signify the temporal evolution of the YSOs and not due to the destruction of protoplanetary atmospheres under the influence of the UV radiation from the OB association.

The bright-rimmed cloud SFO 37, was found to have an an exemplary bow shaped geometry and show a clean evolutionary sequence of YSOs (Ikeda et al. 2008). SFO 38 in contrast has a more complicated geometry. As noted earlier the $H\alpha$ emission from SFO 38 shows an asymmetry relative to the axis connecting the globule to the nearest O star HD 206267. Further, in SFO 38 though the YSOs clearly show an age segregation, they are not distributed along a single straight line. It is however possible to identify another direction along which some of the YSOs are most likely aligned. The asymmetry of $H\alpha$ emission and the non-linearity of the distribution of YSOs suggest that the evolution of SFO 38 is influenced by the nearby B star HD 206773 as well. From the $H\alpha$ line image (Figure 2) HD 206773 seems to be ionizing the eastern part of the rim more efficiently than the extent to which HD 206267 has ionized the western part of the rim. Using the ^{13}CO $J = 1-0$ map of SFO 38, Patel et al. (1995) also found that the eastern and western wings of SFO 38 differ in velocity by about 1.5 km s^{-1} relative to the velocity of the dense core of the globule. This suggests that HD 206773 plays an active role in the present dynamics of the globule.

We have identified a spatio-temporal gradient along the directions of both HD 206267 and HD 206773. However the spatial gradient is not continuous, there is a distinguishable gap between the two classes of YSOs e.g. the projected distance of Class I/II sources from the approximate center of the distribution of Class I sources is ~ 0.3 pc and this gap can be interpreted as due to the difference in the arrival times of the shock within the framework of the RDI model. If we consider the age spread to be \sim a few Myr (comparing the estimated ages from SED fitting and optical CMD) and the spatial separation between the MIR-50 (Class 0/I) and MIR-29 (Class II) to be ~ 0.6 pc, we obtain the speed of shock propagation to be $0.1-0.3 \text{ km s}^{-1}$. The estimated shock speed is consistent with the shock velocities obtained from 3-D numerical simulations (Miao et al. 2006). The estimated speed of shock propagation are approximate since we use only projected distances between sources and do not consider the time lapse between the arrival of the shockwave and the triggering of star formation in the globule, which from simulations is ~ 0.375 Myr (Miao et al. 2006).

Thus, our observations and subsequent estimate of the evolutionary stages of the YSOs embedded in SFO 38, are consistent with a scenario of triggered star formation via the RDI mechanism powered by two different ionizing sources, HD 206267 and HD 206773.

5. Summary

We have presented multiwavelength photometric study of SFO 38 from optical *BVRI* to *Spitzer* IRAC and MIPS observations along with optical spectroscopy of the selected objects. We summarize

our work as follows.

- A total of 40 YSOs (Classes 0/I/II) and 13 YSO candidates are identified based on MIR color indices and we also confirm H α emission from 2 YSOs which are not known in the literature. We further identify 4 additional YSOs based on H α emission and thus we find 44 YSOs in and around SFO 38.
- H α emission line YSOs are mostly K–M type stars with an age spread of 1-8 Myr and mass range of .3-2.2 M $_{\odot}$. Some of the YSOs show photometric variation in optical and NIR bands and also variable H α emission in the medium resolution spectra. Mass accretion rates estimated from broad H α line profiles are of the order of 10 $^{-8}$ to 10 $^{-10}$ M $_{\odot}$ yr $^{-1}$.
- Mass, luminosity and age for the different components of the protostellar cluster at IRAS 21391+5802 were derived by SED fitting.
- Continuum subtracted H α line image show asymmetric H α emission at the bright-rim. Two OB type stars e.g. HD 206267 (O6.5) and HD 206773 (B0V) are proposed as the potential ionizing sources.
- Class II to Class 0/I objects are distributed from the rim to the core part of the globule respectively. It is possible to identify at least two different axes of elongation of the YSO distribution. The spatial gap between the two different classes of YSOs is consistent with the difference in the arrival time of a shockwave propagating into the globule. The spatio-temporal gradient in the distribution of YSOs along two different axes that are parallel to one of the either ionizing star indicate triggered star formation due to the Radiation Driven Implosion model.

This work is based [in part] on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. This research has made use of the SIMBAD data base, operated at CDS, Strasbourg, France. This publication makes use of the data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. RC would like to thank Dr. P. S. Parihar and Ramya S. for useful discussions.

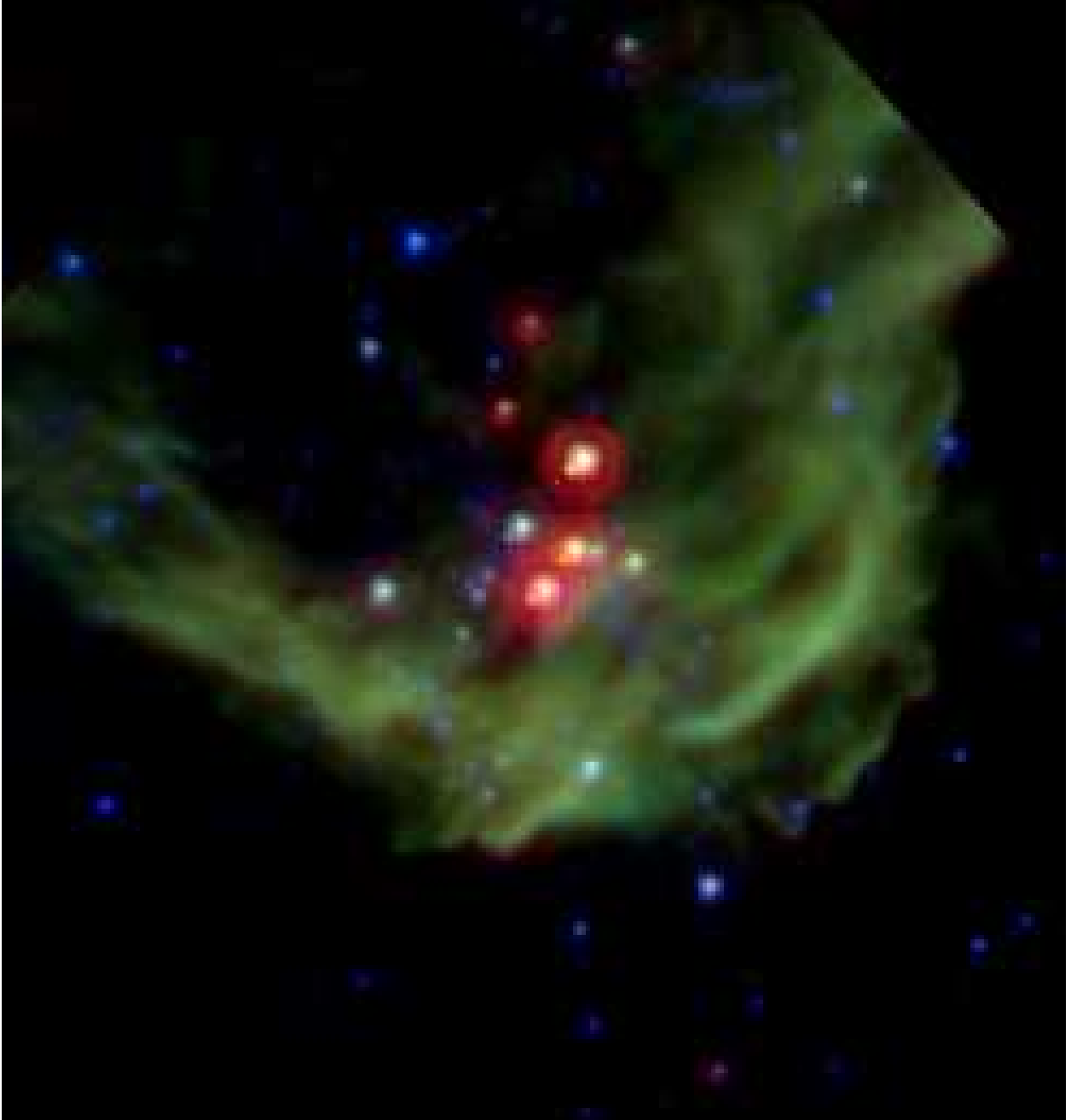


Fig. 1.— IRAC-MIPS color-composite image of SFO 38 using $3.6 \mu\text{m}$ (Blue), $8 \mu\text{m}$ (Green) and $24 \mu\text{m}$ (Red). The image is centered at $\alpha_{2000} = 21^{\text{h}}40^{\text{m}}42^{\text{s}}$ and $\delta_{2000} = 58^{\circ}16'10''$ and extends over $5' \times 5'$ ($\alpha \times \delta$).

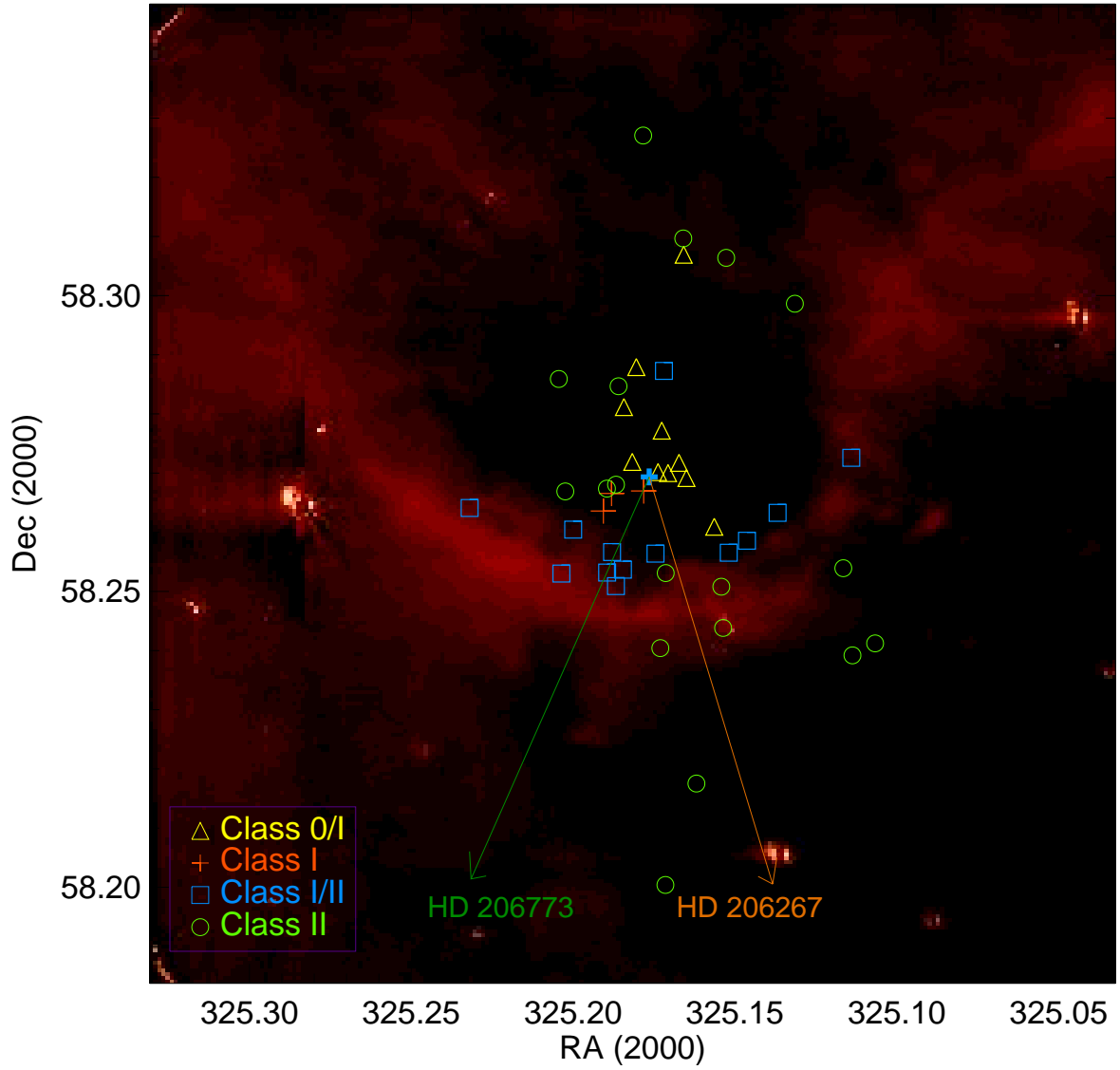


Fig. 2.— Continuum subtracted H α emission line image of SFO 38. Class 0/I to Class II YSOs are overplotted with different symbols. The directions towards HD 206267 and HD 206773 are marked with two different *arrows*.

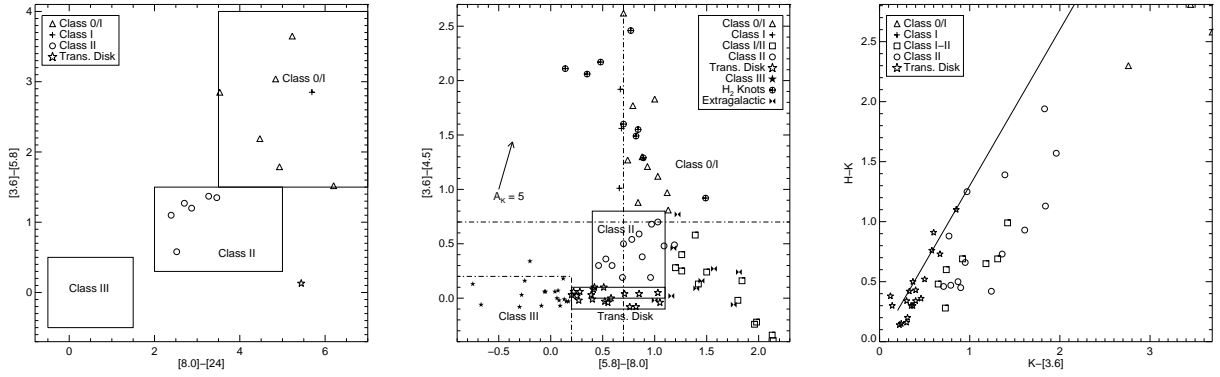


Fig. 3.— Color-color diagrams for all MIR sources. Approximate classification criteria adopted from Megeath et al. (2004), Fang et al. (2009) and Muzerolle et al. (2004) are shown in the two panels. (a) MIR color-color diagram based on *Spitzer* 3-band IRAC and MIPS photometry and (b) 4 band IRAC color-color diagram. Dashed lines in the two panels are taken from Hartmann et al. (2005). Reddening vector corresponding to the extinction laws given by the fitted function from Indebetouw et al. (2005) is shown in (b). The dashed lines $[3.6]-[4.5] = 0.7$, $[4.5]-[5.8] = 0.7$ and $[5.8]-[8.0] = 0.7$ discriminate Class II sources from Class I/0 sources, and $[3.6]-[4.5] = 0.2$, $[4.5]-[5.8] = 0.2$ and $[5.8]-[8.0] = 0.2$ discriminate Class III from Class II and Transitional Disk sources. (c) NIR and *Spitzer* MIR color-color diagram. *Solid* line is the reddening vector due to interstellar extinction (Tapia 1981). Sources to the right of the reddening vector are YSOs with NIR excess.

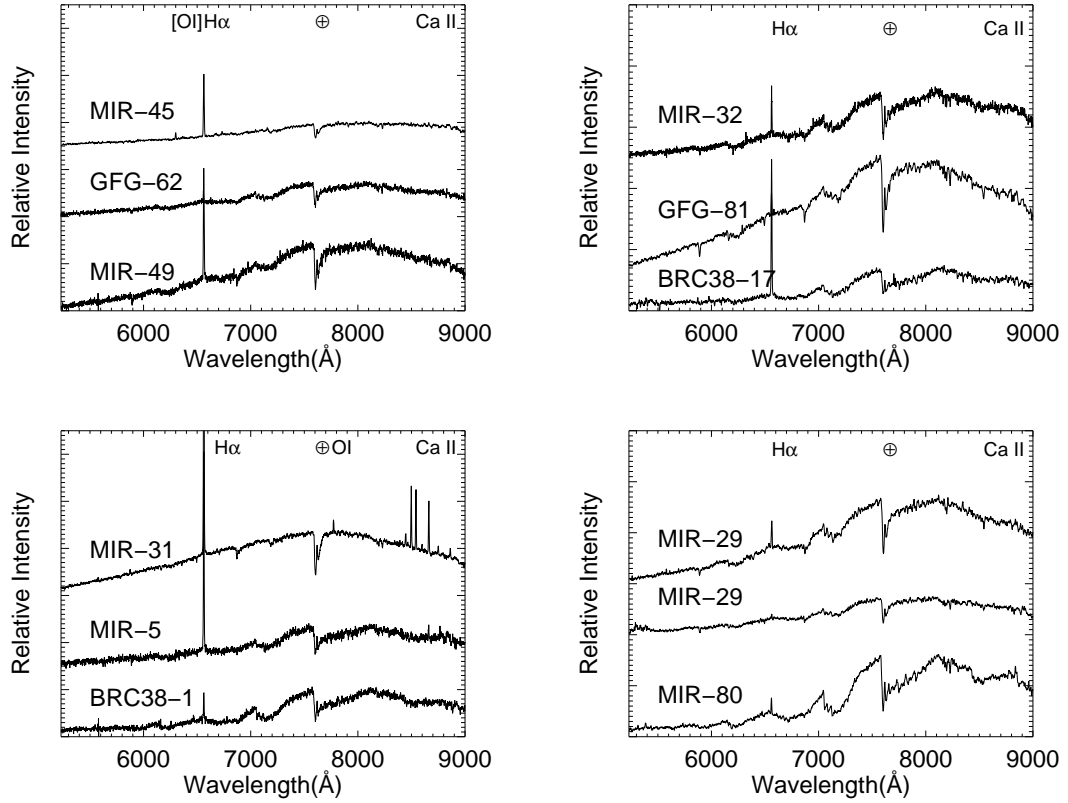


Fig. 4.— Sample spectra of YSOs in SFO 38 obtained with *HFOSC* instrument. The strong features e.g. $H\alpha$ emission ($\lambda 6563\text{\AA}$), CaII infrared triplet emission, OI line at $\lambda 7773\text{\AA}$ and [OI] line at $\lambda 6300\text{\AA}$ are marked in the spectra. Atmospheric features are indicated with \oplus . Two spectra of MIR-29 taken at two different epochs show variable $H\alpha$ emission (see text for details).

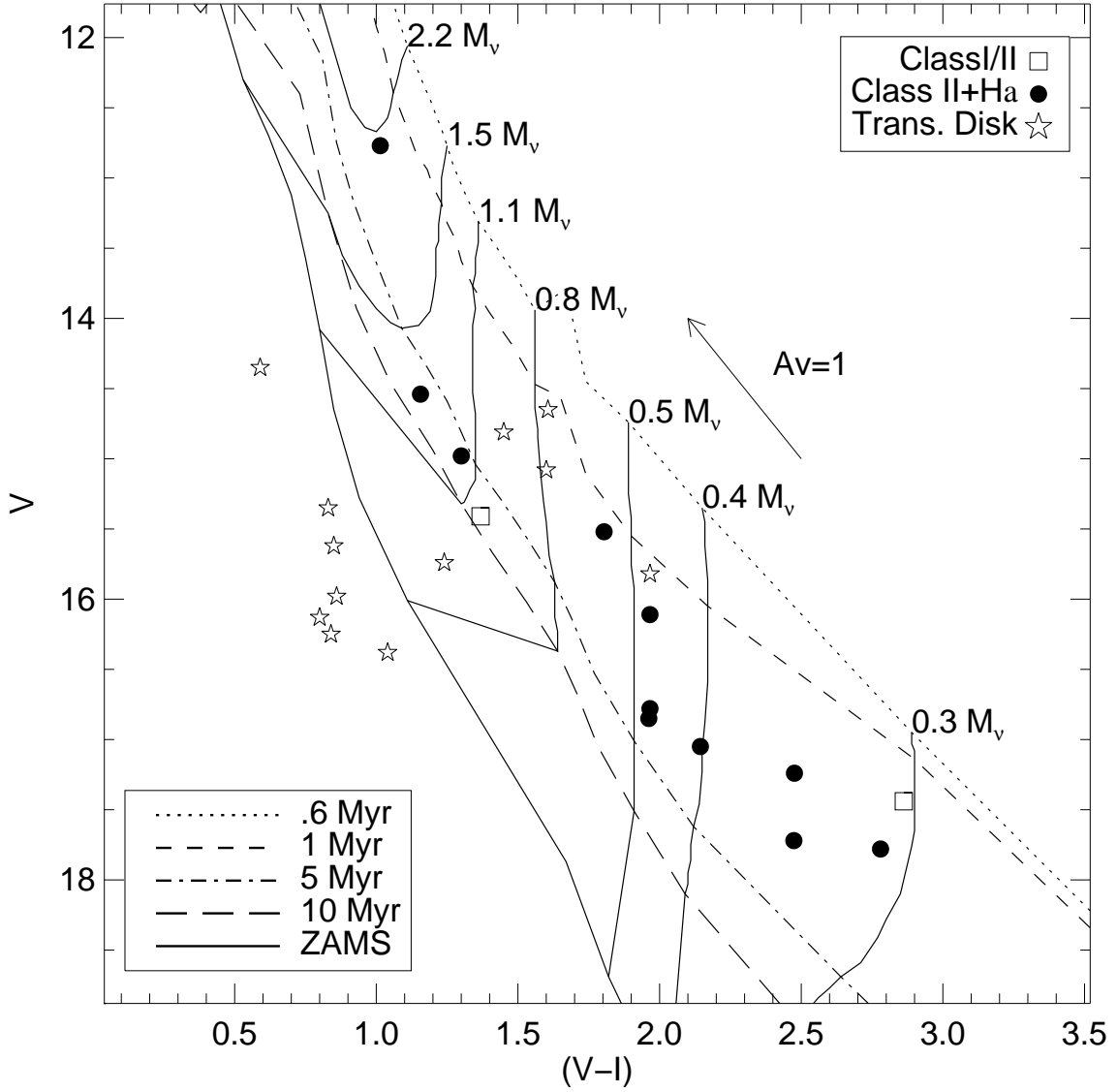


Fig. 5.— Extinction corrected V vs. V-I Color-Magnitude diagram of YSOs near SFO 38. $H\alpha$ emission YSOs are shown by *filled circles*. The ZAMS and 0.6, 1, 5, 10 Myr isochrones of Siess et al. (2000) are shown with the evolutionary tracks for masses from 0.3 to 2.2 M_{\odot} , at an adopted distance of 750 pc.

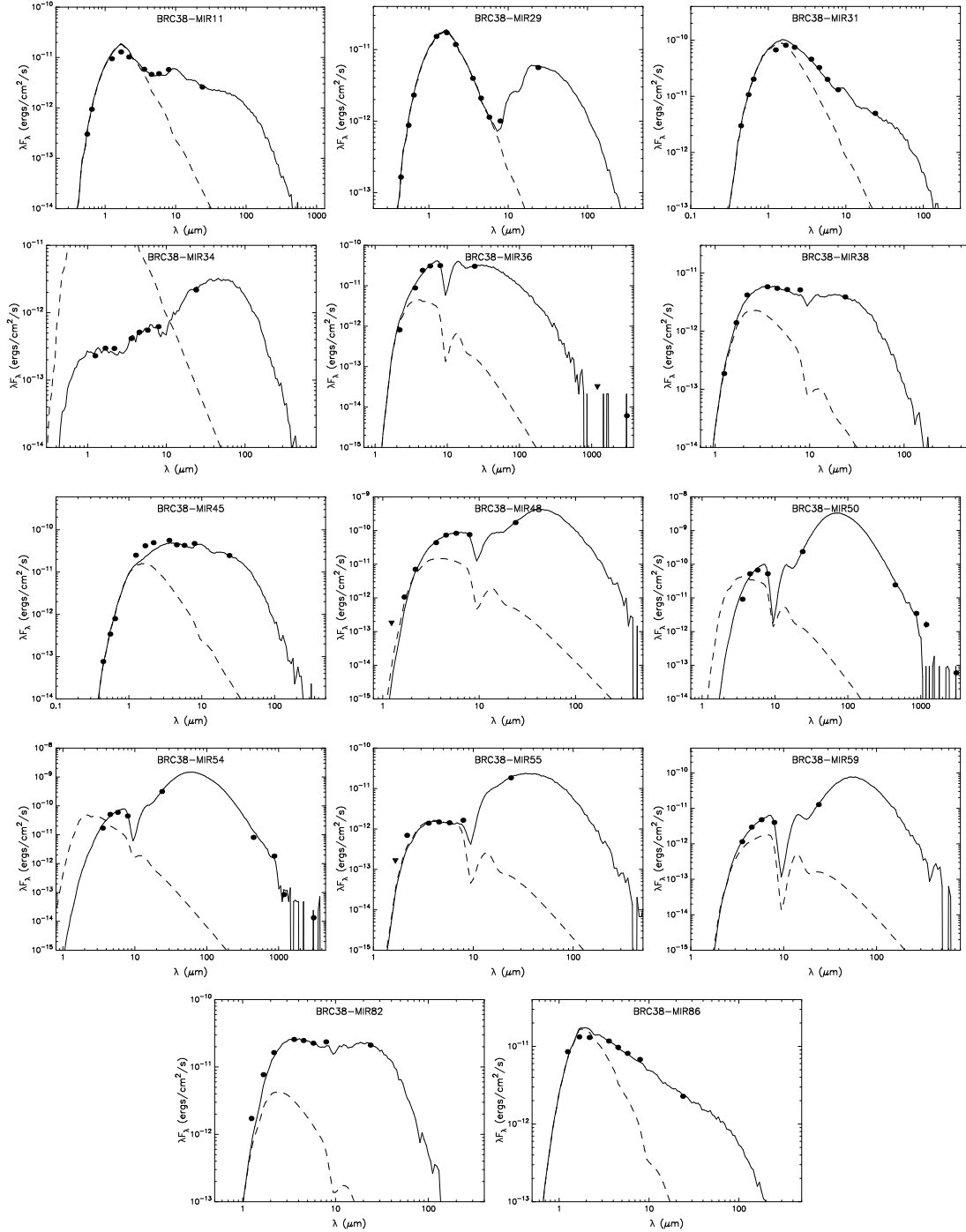


Fig. 6.— SED fits for the PMS objects using axisymmetric radiation transfer models. The filled circles indicate the measured fluxes and uncertainties. The filled triangles correspond to the upper limits of flux at these wavelengths. The continuous black line represents the best-fitting SED, and the dashed line shows the stellar photosphere corresponding to the central source of the best fitting model, in the absence of circumstellar dust (but including interstellar extinction).

Table 1. Results of Near- & Mid-IR photometry of the Mid-infrared sources in SFO 38

Source SFO38	α_{2000}	δ_{2000}	J	H	K_s	$F_{3.6}$ mJy	$F_{4.5}$ mJy	$F_{5.8}$ mJy	$F_{8.0}$ mJy	F_{24} mJy	Class	Comments
MIR-1	21:40:24.97	58:16:10.5	14.48±0.04	13.72± 0.05	13.42± 0.05	1.67±0.01	1.10±0.01	0.96±0.02	1.03±0.02	...	Trans.	JHK_s^c
MIR-2	21:40:25.39	58:15:47.3	15.35±0.06	14.51± 0.07	14.15± 0.07	0.94±0.01	0.63±0.01	0.68±0.02	0.98±0.02	...	Trans.	...
MIR-3	21:40:25.84	58:15:26.1	15.62±0.07	14.80± 0.07	14.62± 0.10	0.52±0.01	0.31±0.00	0.23±0.02	0.07±0.02	...	III/S	...
MIR-4	21:40:26.84	58:14:51.8	16.26±0.10	15.67± 0.15	15.06± 0.15	0.32±0.00	0.20±0.00	0.17±0.02	0.11±0.02	...	III/S	...
MIR-5	21:40:27.29	58:14:21.14	14.30±0.04	13.30± 0.04	12.88± 0.04	6.22±0.05	...	...	...	...	II	H α , X-ray
MIR-6	21:40:27.38	58:16:21.3	...	...	...	0.07±0.00	0.03±0.00	0.51±0.02	2.00±0.03	...	I/II	...
MIR-7	21:40:27.97	58:15:14.1	14.51±0.04	13.41± 0.04	12.94± 0.04	3.89±0.02	3.52±0.02	3.44±0.03	4.33±0.03	...	II	H α , J
MIR-8	21:40:28.35	58:16:42.3	11.59±0.03	10.78± 0.03	10.43± 0.02	23.62±0.07	14.18±0.04	10.94±0.06	6.63±0.04	...	III/S	...
MIR-9	21:40:30.63	58:15:00.0	15.31±0.05	14.90± 0.07	14.70± 0.11	0.49±0.01	0.32±0.01	0.28±0.01	0.22±0.02	...	Trans.	...
MIR-10	21:40:31.00	58:15:09.2	13.44±0.03	12.97± 0.04	12.79± 0.04	2.61±0.02	1.63±0.01	1.29±0.02	...	...	III/S	...
MIR-11	21:40:31.56	58:17:55.1	14.03±0.03	12.89± 0.03	12.39± 0.03	6.93±0.03	6.93±0.03	9.15±0.06	15.17±0.12	20.46±0.08	II	H α , X-ray, JHK_s
MIR-12	21:40:31.97	58:14:56.0	16.72±0.16	15.78± 0.15	15.41± 0.21	0.41±0.00	0.28±0.00	0.26±0.01	...	...	III/S	...
MIR-13	21:40:32.23	58:16:53.6	14.13±0.03	12.44± 0.04	11.71± 0.03	10.82±0.04	6.39±0.02	6.54±0.05	7.36±0.05	...	Trans.	...
MIR-14	21:40:32.46	58:13:47.2	13.40±0.03	12.83± 0.03	12.63± 0.03	2.78±0.03	...	1.30±0.05	...	...	III/S	...
MIR-15	21:40:32.71	58:17:23.5	12.19±0.03	11.55± 0.03	11.36± 0.03	9.21±0.04	5.50±0.02	4.04±0.04	1.71±0.04	...	III/S	...
MIR-16 ^b	21:40:32.84	58:15:47.8	17.42±0.01	16.61±0.01	16.09±0.01	1.42±0.01	0.73±0.01	9.50±0.05	32.10±0.11	...	I/II	...
MIR-17	21:40:33.64	58:14:44.6	16.54±0.14	15.81± 0.18	15.07± 0.00	0.21±0.00	0.13±0.00	0.11±0.01	0.16±0.02	...	Galaxy	...
MIR-18	21:40:33.69	58:14:59.5	13.06±0.03	12.09± 0.03	11.75± 0.02	8.13±0.03	4.82±0.02	4.72±0.04	5.60±0.03	...	Trans.	...
MIR-19	21:40:34.05	58:18:08.1	15.70±0.06	13.40± 0.04	12.30± 0.02	7.41±0.03	5.16±0.02	4.95±0.04	4.03±0.04	...	Trans.	...
MIR-20	21:40:34.30	58:18:23.6	...	...	...	0.31±0.00	0.84±0.01	1.03±0.02	1.24±0.04	...	H ₂	...
MIR-21	21:40:34.59	58:16:11.4	...	...	...	0.08±0.00	0.05±0.00	1.33±0.03	...	...	III/S	...
MIR-22 ^b	21:40:34.76	58:15:20.9	17.70±0.01	16.68±0.01	16.04±0.01	0.25±0.01	0.34±0.01	...	...	...	III/S	...
MIR-23	21:40:34.79	58:16:10.8	...	...	...	...	...	4.47±0.05	...	...	...	...
MIR-24	21:40:35.02	58:18:22.2	16.48±...	15.72±...	14.90± 0.21	0.62±0.01	2.68±0.01	1.84±0.03	1.42±0.03	...	H ₂	...
MIR-25 ^b	21:40:35.11	58:15:30.9	18.21±0.02	16.85±0.01	16.16±0.02	0.92±0.01	0.48±0.01	5.32±0.04	18.26±0.08	...	I/II	...
MIR-26	21:40:35.20	58:14:05.0	13.11±0.03	12.61± 0.03	12.45± 0.03	3.55±0.02	2.40±0.01	1.59±0.02	0.84±0.02	...	III/S	...
MIR-27	21:40:35.68	58:18:21.3	16.55±...	15.73±...	14.79± 0.17	0.77±0.01	3.61±0.02	2.20±0.03	1.91±0.03	...	H ₂	...
MIR-28	21:40:36.46	58:15:23.6	15.97±0.10	14.73± 0.08	14.04± 0.07	2.27±0.01	1.43±0.01	6.68±0.04	19.47±0.08	...	I/II	...
MIR-29	21:40:36.52	58:13:45.8	13.51±0.02	12.58± 0.03	12.24± 0.03	4.69±0.02	3.14±0.01	2.17±0.03	2.64±0.03	44.29±0.09	Trans.	H α , X-ray
MIR-30	21:40:36.65	58:18:23.0	17.12±...	15.18±0.10	13.93±0.07	1.84±0.01	1.55±0.01	1.42±0.03	1.21±0.03	...	II	...
MIR-31	21:40:36.88	58:14:37.8	11.90±0.02	10.89± 0.03	10.23± 0.02	54.30±0.14	48.79±0.10	38.25±0.12	34.45±0.10	39.36±0.07	II	H α , X-ray
MIR-32	21:40:37.02	58:15:02.9	14.27±0.03	13.28± 0.04	12.82± 0.03	4.01±0.02	3.07±0.01	2.86±0.03	3.87±0.04	...	II	H α , K_s
MIR-33	21:40:37.16	58:15:46.6	17.01±...	15.80±0.16	14.55±0.10	1.33±0.01	1.28±0.01	0.71±0.03	...	...	III/S	...
MIR-34 ^b	21:40:37.54	58:15:39.3	18.07±0.02	16.98±0.01	16.24±0.02	0.49±0.01	0.77±0.01	1.05±0.03	1.63±0.04	17.15±0.06	0/I	...
MIR-35	21:40:39.05	58:16:03.3	...	...	...	0.41±0.01	1.04±0.01	2.19±0.03	...	...	H ₂	...
MIR-36 ^a	21:40:39.60	58:16:09.0	...	>17.6	15.14±0.16	10.47±0.03	36.11±0.08	59.09±0.17	82.89±0.22	239.10±0.10	0/I	X-ray
MIR-37	21:40:39.80	58:18:24.9	...	...	...	0.53±0.01	0.76±0.01	1.15±0.02	1.39±0.03	...	0/I	...
MIR-38	21:40:39.84	58:18:34.8	18.29±...	15.30±0.12	13.36±0.04	6.88±0.03	8.19±0.03	9.95±0.06	13.49±0.06	30.69±0.07	II	X-ray
MIR-39	21:40:40.15	58:16:18.2	...	...	...	1.36±0.01	2.65±0.01	3.24±0.04	4.25±0.05	...	0/I	...
MIR-40	21:40:40.43	58:18:26.1	18.28±...	15.64±0.15	13.85 ±0.06	2.35±0.01	2.05±0.01	1.64±0.03	0.76±0.02	...	III/S	...
MIR-41	21:40:40.96	58:16:12.0	17.55±...	15.89±...	13.59± 0.06	13.04±0.04	23.41±0.06	29.43±0.10	42.25±0.15	...	0/I	...
MIR-42	21:40:40.98	58:16:52.4	17.93±...	15.34±0.14	13.93±0.06	1.41±0.01	1.04±0.01	0.83±0.02	0.37±0.03	...	III/S	...
MIR-43	21:40:41.07	58:13:58.9	12.96±0.02	12.08± 0.03	11.77± 0.02	6.80±0.02	4.58±0.02	3.19±0.03	1.84±0.03	...	III/S	H α , X-ray
MIR-44	21:40:41.10	58:17:54.1	14.20±0.04	13.46± 0.04	13.21± 0.03	1.89±0.01	1.14±0.01	0.73±0.02	0.37±0.02	...	III/S	...
MIR-45	21:40:41.14	58:15:11.2	12.97±0.03	11.61± 0.04	10.68± 0.02	66.38±0.17	65.98±0.14	81.84±0.21	124.60±0.31	194.40±0.09	II	H α , X-ray
MIR-46	21:40:41.27	58:17:14.2	...	...	...	0.06±0.00	0.03±0.00	0.65±0.02	2.61±0.03	...	I/II	...
MIR-47	21:40:41.40	58:14:17.5	15.48±...	15.50±0.12	14.63±0.00	0.34±0.00	0.21±0.00	0.16±0.01	0.10±0.02	...	III/S	...
MIR-48	21:40:41.43	58:16:37.8	18.30±...	15.60±0.15	12.79±0.03	51.81±0.14	109.40±0.20	158.50±0.34	199.60±0.44	1362.00±0.26	0/I	...
MIR-49	21:40:41.54	58:14:25.5	13.65±0.03	12.62± 0.03	12.17± 0.03	8.70±0.03	7.38±0.03	6.65±0.04	6.42±0.04	...	II	H α , X-ray

Table 1—Continued

Source SFO38	α_{2000}	δ_{2000}	J	H	K_s	$F_{3.6}$ mJy	$F_{4.5}$ mJy	$F_{5.8}$ mJy	$F_{8.0}$ mJy	F_{24} mJy	Class	Comments
MIR-50	21:40:41.71	58:16:12.6	...	...	...	10.84±0.04	78.01±0.16	128.00±0.29	137.00±0.34	1871.00±0.31	0/I	X-ray
MIR-51	21:40:41.89	58:15:23.0	15.68±0.09	14.30± 0.06	13.65± 0.05	2.88±0.02	2.30±0.01	3.75±0.04	8.33±0.06	...	I/II	X-ray, JHK_s
MIR-52	21:40:41.96	58:13:49.1	15.50±0.06	15.00± 0.09	14.98± 0.14	0.40±0.00	0.27±0.00	0.19±0.01	0.10±0.02	...	III/S	
MIR-53	21:40:42.35	58:18:40.1	...	...	...	0.48±0.00	2.16±0.01	1.99±0.03	1.26±0.02	...	H ₂	
MIR-54	21:40:42.77	58:16:01.1	...	...	...	20.16±0.06	75.86±0.15	113.50±0.27	117.60±0.31	2484.00±0.38	I	X-ray
MIR-55 ^a	21:40:43.32	58:17:16.5	...	>17.6	15.31±0.11	1.65±0.01	2.23±0.01	2.72±0.03	4.31±0.03	145.40±0.08	0/I	
MIR-56	21:40:43.34	58:18:42.6	16.32±0.13	14.42± 0.05	13.55± 0.04	1.93±0.01	1.39±0.01	0.91±0.02	0.26±0.03	...	III/S	
MIR-57	21:40:43.62	58:16:18.8	17.89±...	16.09±...	13.51± 0.07	33.21±0.09	68.55±0.14	82.72±0.21	91.38±0.24	...	0/I	X-ray
MIR-58	21:40:43.65	58:14:18.4	15.55±0.08	15.05± 0.10	14.89± 0.14	0.41±0.00	0.28±0.00	0.19±0.01	0.14±0.02	...	Trans.	
MIR-59	21:40:44.23	58:16:52.2	...	...	...	1.36±0.01	4.43±0.02	9.13±0.05	10.52±0.06	100.90±0.07	0/I	
MIR-60	21:40:44.26	58:14:12.4	15.57±0.06	15.00± 0.09	14.69± 0.12	0.45±0.00	0.30±0.00	0.22±0.01	0.09±0.02	...	III/S	
MIR-61	21:40:44.31	58:15:13.2	16.05±0.10	16.05±0.10	14.59± 0.07	13.60± 0.05	3.78±0.02	4.10±0.02	7.89±0.05	15.74±0.08	I/II	X-ray, JHK_s
MIR-62	21:40:44.64	58:17:04.9	17.83±...	15.75±0.15	14.62±0.10	2.16±0.01	2.38±0.01	2.51±0.03	3.06±0.03	...	II	
MIR-63	21:40:44.82	58:16:05.0	15.86±...	14.28±0.06	12.89±0.05	7.08±0.03	7.17±0.03	6.83±0.05	7.25±0.05	...	II	X-ray, K_s
MIR-64	21:40:44.83	58:15:03.3	14.62±0.04	13.35± 0.04	12.66± 0.03	5.64±0.02	5.23±0.02	7.28±0.05	12.94±0.06	...	I/II	H α , X-ray
MIR-65	21:40:44.89	58:17:47.7	...	...	...	0.42±0.00	2.56±0.01	2.01±0.02	2.29±0.03	...	H ₂	
MIR-66 ^b	21:40:45.11	58:15:24.0	18.46±0.02	16.74±0.01	15.71±0.01	0.59±0.01	0.44±0.01	1.73±0.03	5.26±0.05	...	I/II	
MIR-67	21:40:45.16	58:15:59.6	...	...	...	5.73±0.02	9.26±0.03	11.46±0.06	11.78±0.07	...	I	X-ray
MIR-68 ^b	21:40:45.24	58:16:41.3	17.38±0.01	16.29± 0.01	15.53±0.01	0.43±0.01	0.42±0.01	0.41±0.02	0.68±0.02	...	Galaxy	
MIR-69	21:40:45.29	58:16:53.3	...	...	...	0.53±0.01	0.61±0.01	0.60±0.02	...	...	III/S	
MIR-70 ^b	21:40:45.41	58:16:45.5	20.38±0.15	17.48±0.02	15.96±0.01	0.33±0.00	0.27±0.01	0.48±0.02	1.14±0.02	...	Galaxy	
MIR-71	21:40:45.48	58:15:11.5	14.65±0.05	13.71± 0.06	13.11± 0.04	3.17±0.02	2.61±0.01	3.41±0.04	5.73±0.05	...	I/II	X-ray, K_s
MIR-72	21:40:45.50	58:16:02.6	15.68±0.09	13.73± 0.06	12.85± 0.04	4.13±0.02	3.15±0.02	2.74±0.03	2.88±0.03	...	II	X-ray
MIR-73	21:40:45.76	58:15:48.9	...	...	...	2.71±0.02	7.27±0.03	10.79±0.06	11.29±0.07	...	I	X-ray
MIR-74	21:40:45.82	58:17:43.0	...	...	...	0.36±0.00	0.92±0.01	1.16±0.02	1.38±0.02	...	H ₂	
MIR-75	21:40:46.22	58:17:40.2	...	...	...	0.34±0.00	0.71±0.01	1.20±0.02	1.53±0.02	...	H ₂	
MIR-76	21:40:46.46	58:15:23.0	12.81±0.03	11.95± 0.03	11.65± 0.02	8.66±0.03	5.35±0.02	5.25±0.04	7.74±0.07	...	Trans.	X-ray, H α
MIR-77	21:40:46.86	58:15:33.4	15.30±0.06	13.55± 0.05	12.63± 0.04	5.80±0.02	4.05±0.02	5.16±0.04	10.41±0.08	...	Galaxy	X-ray
MIR-78	21:40:47.35	58:16:37.3	17.08±...	16.14±0.24	14.63±0.10	1.00±0.01	0.75±0.01	0.59±0.02	0.36±0.02	...	III/S	
MIR-79	21:40:47.43	58:17:39.1	11.53±0.03	9.98± 0.03	9.37± 0.02	72.47±0.17	46.36±0.10	34.42±0.11	20.21±0.07	...	III/S	
MIR-80	21:40:48.00	58:15:37.6	13.89±0.03	12.95± 0.03	12.67± 0.03	4.72±0.02	3.39±0.02	5.77±0.04	11.90±0.06	...	I/II	H α , X-ray
MIR-81	21:40:48.52	58:16:37.1	16.18±0.09	14.95± 0.08	14.46± 0.08	0.71±0.01	0.46±0.01	0.38±0.02	0.62±0.02	...	Galaxy	K_s
MIR-82	21:40:48.58	58:16:00.9	15.88±0.09	13.45± 0.04	11.88± 0.02	30.35±0.08	37.01±0.08	43.12±0.13	61.94±0.17	167.10±0.09	II	JH
MIR-83	21:40:48.84	58:16:22.8	16.02±0.12	15.25± 0.13	14.46± 0.08	0.61±0.01	0.43±0.01	0.25±0.02	...	...	III/S	
MIR-84	21:40:48.87	58:15:10.9	15.64±0.06	15.04± 0.08	14.56± 0.09	0.77±0.01	0.62±0.01	0.75±0.02	1.34±0.03	...	I/II	H α , JK_s
MIR-85	21:40:49.05	58:17:19.4	15.79±0.08	13.83± 0.05	12.92± 0.02	3.32±0.02	2.19±0.01	1.75±0.02	1.18±0.02	...	Trans.	J
MIR-86	21:40:49.06	58:17:09.3	14.14±0.03	12.86± 0.04	12.13± 0.02	13.88±0.05	14.57±0.04	15.54±0.07	17.83±0.07	17.99±0.05	II	H α , X-ray, K_s
MIR-87	21:40:49.29	58:14:11.3	13.52±0.03	12.66± 0.03	12.35± 0.02	3.87±0.02	2.44±0.01	1.66±0.02	0.99±0.02	...	III/S	
MIR-88	21:40:49.67	58:17:37.3	17.13±0.23	14.99± 0.09	14.23± 0.07	1.07±0.01	0.73±0.01	0.60±0.02	0.36±0.02	...	III/S	
MIR-89 ^b	21:40:51.07	58:16:24.3	17.80±0.01	16.70±0.01	16.09±0.01	0.11±0.00	0.08±0.00	0.11±0.02	0.23±0.02	...	Galaxy	
MIR-90	21:40:51.23	58:16:38.9	14.23±0.03	13.76± 0.04	13.61± 0.04	1.26±0.01	0.78±0.01	0.57±0.02	0.53±0.02	...	Trans.	HK
MIR-91	21:40:51.81	58:16:29.1	15.70±0.06	14.45± 0.06	13.93± 0.07	1.19±0.01	0.74±0.01	0.60±0.02	0.54±0.02	...	Trans.	HK
MIR-92	21:40:51.90	58:17:01.6	...	...	...	0.36±0.00	0.33±0.00	0.20±0.02	...	...	III/S	
MIR-93 ^b	21:40:51.97	58:16:23.6	19.21±0.06	17.47±0.01	16.39±0.01	0.16±0.00	0.10±0.00	0.23±0.02	0.65±0.02	...	Galaxy	
MIR-94	21:40:52.26	58:17:46.0	15.68±0.05	14.56± 0.05	14.06± 0.06	0.94±0.01	0.65±0.01	0.59±0.02	0.48±0.03	...	Trans.	
MIR-95	21:40:52.98	58:18:01.1	15.29±0.05	14.59± 0.06	14.22± 0.07	0.84±0.01	0.53±0.01	0.54±0.03	0.34±0.03	...	III/S	
MIR-96	21:40:53.12	58:14:57.4	14.77±0.06	14.25± 0.07	13.95± 0.07	0.84±0.01	0.54±0.01	0.38±0.02	0.37±0.03	...	Trans.	
MIR-97	21:40:53.42	58:14:51.9	15.50±0.06	14.88± 0.09	14.74± 0.11	0.44±0.00	0.31±0.01	0.23±0.01	0.20±0.02	...	Trans.	
MIR-98	21:40:53.68	58:16:41.2	...	...	...	0.25±0.00	0.71±0.01	0.79±0.02	0.83±0.02	...	H ₂	

Table 1—Continued

Source SFO38	α_{2000}	δ_{2000}	J	H	K_s	$F_{3.6}$ mJy	$F_{4.5}$ mJy	$F_{5.8}$ mJy	$F_{8.0}$ mJy	F_{24} mJy	Class	Comments
MIR-99	21:40:55.68	58:15:50.8	...	...	...	0.36±0.00	0.14±0.00	2.69±0.03	9.65±0.05	...	I/II	
MIR-100	21:40:55.87	58:14:16.3	14.18±0.03	13.61± 0.04	13.39± 0.04	...	0.87±0.02	...	0.45±0.03	...	III/S	
MIR-101	21:40:55.88	58:15:34.8	...	...	...	0.25±0.00	0.32±0.00	0.41±0.02	0.71±0.02	...	Galaxy	
MIR-102	21:40:55.93	58:17:07.8	14.45±0.03	13.19± 0.04	12.76± 0.03	3.21±0.02	2.01±0.01	1.39±0.02	0.99±0.02	...	Trans.	
MIR-103	21:40:57.04	58:16:56.8	16.61±0.13	15.92± 0.21	16.22± 0.00	0.42±0.01	0.34±0.00	0.40±0.02	1.19±0.03	...	Galaxy	
MIR-104	21:40:57.06	58:16:29.0	14.73±0.03	13.00± 0.03	12.24± 0.02	6.10±0.02	4.11±0.02	2.87±0.03	1.96±0.03	...	Trans.	
MIR-105	21:40:57.33	58:16:41.7	16.64±...	15.41±...	14.55± 0.13	0.79±0.01	1.18±0.01	2.90±0.03	6.34±0.04	...	H ₂	
MIR-106	21:40:57.50	58:14:43.6	15.00±0.04	14.66± 0.07	14.34± 0.09	...	0.43±0.01	0.25±0.03	0.15±0.02	...	III/S	
MIR-107	21:40:58.03	58:15:12.1	15.06±0.05	14.50± 0.07	14.12± 0.08	0.70±0.01	0.46±0.01	0.30±0.02	0.21±0.02	...	Trans.	
MIR-108	21:40:58.45	58:16:20.5	13.11±0.03	12.44± 0.03	12.02± 0.03	5.93±0.03	3.77±0.02	3.13±0.03	2.52±0.03	...	Trans.	
MIR-109	21:40:58.53	58:15:00.3	12.15±0.03	11.26± 0.03	10.96± 0.02	...	8.34±0.03	5.73±0.05	3.46±0.03	...	III/S	
MIR-110	21:40:59.71	58:17:33.3	12.69±0.02	11.25± 0.03	10.59± 0.02	24.86±0.17	...	10.77±0.13	...	...	III/S	

^a JHK_s photometry from Nisini et al. (2001)

^b JHK_s photometry from Beltrán et al. (2009)

^cVariable in $J/H/K_s$

Table 2. Coordinates and flux densities of NIR & IRAC 3.6/4.5 μm PMS sources in SFO 38

Source SFO38	α_{2000}	δ_{2000}	J	H	K_s	$F_{3.6}$ mJy	$F_{4.5}$ mJy
NIR-1	21:40:34.36	58:16:19.2	20.88 \pm ...	18.12 \pm 0.03	16.68 \pm 0.02	15.73 \pm 0.03	15.38 \pm 0.03
NIR-2	21:40:36.46	58:16:28.7	20.84 \pm ...	19.31 \pm 0.10	17.14 \pm 0.03	15.23 \pm 0.02	14.75 \pm 0.02
NIR-3	21:40:37.57	58:16:01.2	20.80 \pm ...	19.98 \pm ...	17.35 \pm ...	15.22 \pm 0.03	14.29 \pm 0.02
NIR-4	21:40:38.17	58:15:32.7	20.87 \pm ...	18.32 \pm 0.03	16.72 \pm 0.02	14.84 \pm 0.02	14.59 \pm 0.02
NIR-5	21:40:39.53	58:15:46.9	...	...	...	14.22 \pm 0.01	13.72 \pm 0.01
NIR-6	21:40:39.65	58:15:06.6	16.59 \pm 0.01	15.88 \pm 0.01	15.52 \pm 0.01	14.07 \pm 0.01	13.82 \pm 0.01
NIR-7	21:40:42.81	58:15:45.3	16.29 \pm 0.00	15.38 \pm 0.00	14.77 \pm 0.00	13.91 \pm 0.01	13.27 \pm 0.01
NIR-8	21:40:44.15	58:15:49.6	...	...	...	15.78 \pm 0.04	13.83 \pm 0.01
NIR-9	21:40:44.57	58:15:51.6	15.97 \pm 0.00	15.23 \pm 0.00	14.71 \pm 0.00	14.28 \pm 0.02	13.68 \pm 0.01
NIR-10	21:40:45.85	58:15:40.6	18.70 \pm 0.03	17.09 \pm 0.01	16.01 \pm 0.01	14.68 \pm 0.02	14.18 \pm 0.02
NIR-11	21:40:48.28	58:16:18.8	18.17 \pm 0.02	17.16 \pm 0.01	16.40 \pm 0.02	15.63 \pm 0.03	15.24 \pm 0.03
NIR-12	21:40:50.55	58:16:01.8	20.84 \pm ...	19.65 \pm 0.10	17.55 \pm 0.03	15.65 \pm 0.03	15.29 \pm 0.03
NIR-13	21:40:51.14	58:17:01.5	20.86 \pm ...	18.74 \pm 0.05	17.23 \pm 0.04	15.99 \pm 0.03	15.68 \pm 0.04

Table 3. *BVRI* photometry of MIR sources in SFO 38

Source	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>	Variability
MIR-1	19.82±0.010	18.24±0.005	17.18±0.004	16.00±0.003	
MIR-2	20.48±0.015	18.88±0.006	17.88±0.008	16.84±0.005	
MIR-3	21.58±0.021	19.58±0.007	18.37±0.006	17.14±0.004	
MIR-4	0.00±0.000	20.38±0.016	19.15±0.007	17.73±0.006	
MIR-5	21.11±0.015	19.32±0.007	17.77±0.004	16.37±0.002	<i>BVI</i>
MIR-7	21.59±0.021	19.39±0.006	17.90±0.004	16.38±0.002	
MIR-8	17.74±0.001	15.74±0.001	14.55±0.001	13.35±0.001	
MIR-9	19.95±0.017	18.48±0.004	17.60±0.005	16.62±0.004	
MIR-10	17.28±0.001	16.07±0.001	15.29±0.001	14.49±0.001	
MIR-11	0.00±0.000	19.52±0.011	17.94±0.007	16.19±0.005	
MIR-14	17.67±0.001	16.24±0.001	15.38±0.001	14.53±0.001	
MIR-15	16.89±0.001	15.26±0.001	14.33±0.001	13.44±0.001	
MIR-18	19.62±0.006	17.58±0.003	16.30±0.002	14.98±0.009	
MIR-26	17.34±0.001	16.03±0.001	15.20±0.001	14.30±0.001	
MIR-29	20.58±0.011	18.43±0.005	16.94±0.002	15.42±0.002	
MIR-31	17.43±0.002	15.71±0.001	14.60±0.001	13.52±0.001	
MIR-32	21.15±0.015	19.29±0.006	18.01±0.007	16.25±0.002	<i>BVI</i>
MIR-43	19.41±0.004	17.49±0.002	16.21±0.001	14.73±0.001	<i>BVI</i>
MIR-44	19.36±0.006	17.65±0.003	16.57±0.001	15.51±0.002	
MIR-45	21.41±0.018	19.45±0.007	18.10±0.012	16.33±0.002	<i>BVI</i>
MIR-47	0.00±0.000	19.86±0.009	18.76±0.005	17.61±0.005	
MIR-49	20.91±0.012	18.81±0.004	17.04±0.003	15.69±0.001	<i>BVI</i>
MIR-52	19.54±0.008	18.32±0.005	17.52±0.003	16.64±0.005	
MIR-58	20.13±0.007	18.75±0.003	17.86±0.005	16.91±0.003	<i>B</i>
MIR-60	20.79±0.011	19.13±0.005	18.07±0.005	17.06±0.003	
MIR-64	0.00±0.000	20.49±0.014	18.77±0.016	17.09±0.006	
MIR-76	19.08±0.006	17.16±0.002	15.90±0.002	14.55±0.001	
MIR-79	21.41±0.024	18.56±0.004	16.52±0.002	14.55±0.001	
MIR-80	21.69±0.023	19.81±0.008	17.90±0.006	16.00±0.004	<i>V</i>
MIR-87	19.72±0.005	17.72±0.002	16.50±0.002	15.28±0.002	
MIR-90	18.15±0.002	16.85±0.002	16.04±0.001	15.26±0.002	
MIR-95	0.00±0.000	20.16±0.012	18.71±0.009	17.34±0.004	
MIR-96	19.23±0.008	17.85±0.003	16.94±0.003	16.02±0.002	
MIR-97	20.06±0.007	18.63±0.005	17.76±0.005	16.83±0.004	
MIR-100	18.31±0.003	16.86±0.002	16.03±0.001	15.28±0.002	
MIR-106	18.87±0.004	17.75±0.003	16.96±0.003	16.21±0.002	
MIR-107	19.50±0.004	18.12±0.002	17.22±0.003	16.27±0.002	
MIR-108	18.94±0.005	17.31±0.004	16.13±0.003	14.86±0.001	
MIR-109	18.17±0.003	16.17±0.001	15.00±0.001	13.86±0.001	
MIR-110	0.00±0.000	19.78±0.010	17.76±0.004	15.76±0.003	<i>V</i>
BRC38 1	0.00±0.000	20.05±0.017	18.24±0.009	16.45±0.003	
BRC38 17	0.00±0.000	20.51±0.017	18.65±0.005	16.92±0.006	<i>V</i>
GFG 64	19.01±0.007	17.48±0.003	16.19±0.001	15.18±0.001	
IPHAS	0.00±0.000	20.28±0.011	18.28±0.009	16.50±0.004	

Table 4. Spectral Classification of YSOs

ID	Alt. ID	Date	W_λ (Å)	Sp. Type (±subtype)	T_{eff} (K)	Type	$H\alpha[10\%]$ (km s ⁻¹)	$\log \dot{M}_{ac}$ (M _⊙ yr ⁻¹)	α_{IRAC}	E(V-I)	A_V	E(V-I)/E(B-V)
BRC 38 1		5/10/08	-12.93	M3±1	3470	CTTS	312.23	-9.86		1.13	2.81	
		10/10/09	-16.24				205.29	-10.90				
MIR-5	BRC 38 2	5/10/08	-85.23	M1±1	3720	CTTS	359.79	-9.40		0.99	2.47	3.19
		10/10/09	-106.1				244.53	-10.52				
MIR-7	BRC 38 3	6/10/08	-19.0	M1±2	3720	CTTS	476.25	-8.27	-0.87	1.05	2.61	1.46
		10/10/09	-18.75				463.50	-8.39				
MIR-11	BRC 38 4	10/09/08	-7.30	M1±2	3720	WTTS			0.02	1.37	3.41	
		18/07/09	-11.29									
MIR-29	BRC 38 5	6/09/08	-3.42	M1±2	3720	WTTS			-1.74	1.05	2.61	1.57
		3/11/08	-8.84				469.90	-8.33				
		24/08/09	-1.89									
		9/11/09	-2.74									
MIR-31	BRC 38 6	6/09/08	-53.47	K2±1	4900	CTTS	384.43	-9.16	-1.60	1.18	2.94	1.42
		24/08/09	-57.32				442.02	-8.60				
		9/10/09	-60.5				382.26	-9.18				
MIR-32	BRC 38 7	10/09/08	-33.12	M2±1	3580	CTTS	368.03	-9.32	-1.03	0.90	2.24	2.65
		12/09/09	-15.78				220.59	-10.75				
MIR-43	GFG 62	18/07/09	-3.516	M1±1	3720	WTTS			-2.61	0.80	1.99	1.82
MIR-45	BRC 38 9	6/09/08	-37.43	K4±1	4590	CTTS	281.09	-10.16	-0.18	1.97	4.91	2.21
		3/11/08	-41.22				389.74	-9.11				
		24/08/09	-56.33				273.39	-10.24				
MIR-49	BRC 38 10	4/11/08	-13.5	M0±1	3850	CTTS	430.70	-8.71	-1.37	1.32	3.29	1.91
		9/10/09	-30				450.55	-8.52				
MIR-64	BRC 38 11	10/09/08	-31.46	K5±1	4350	CTTS	239.20	-10.57	0.10	2.04	5.08	
		12/09/09	-25.06									
MIR-76	GFG 81	18/07/09	-3.261	K7±1	4060	WTTS			-1.07	1.01	2.51	1.87
		10/10/09	-3.135									
MIR-80	BRC 38 12	24/08/09	-8.404	M4±1	3370	WTTS			0.31	0.95	2.37	3.39
BRC 38 17		11/11/09	-119.	M3±2	3470	CTTS	205.29	-10.90		1.12	2.79	

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Table 5. Parameters derived from SED modeling using axisymmetric radiation transfer models for the candidate YSOs. A_v refers to the foreground extinction towards the source.

Source	T_* K	M_* M_\odot	M_{disk} M_\odot	M_{env} M_\odot	\dot{M}_{env} $M_\odot \text{ yr}^{-1}$	\dot{M}_{disk} $M_\odot \text{ yr}^{-1}$	L L_\odot	A_v	Age Myr
MIR-11	4442	1.26	6.44×10^{-3}	6.39×10^{-5}	0.0	2.10×10^{-9}	1.27	5.3	3.2
MIR-29	4837	1.55	1.66×10^{-3}	6.13×10^{-7}	0.0	1.16×10^{-9}	1.67	4.4	5.8
MIR-31	5923	1.88	1.33×10^{-4}	7.04×10^{-8}	0.0	2.41×10^{-9}	8.92	4.2	6.7
MIR-34	4523	1.53	7.64×10^{-5}	2.56×10^{-3}	1.21×10^{-8}	1.28×10^{-10}	5.8	3.2	0.69
MIR-36	5413	3.29	4.37×10^{-3}	1.85×10^{-8}	0.0	4.80×10^{-8}	29.1	49.6	1.3
MIR-38	7854	1.98	3.10×10^{-5}	2.99×10^{-6}	0.0	5.49×10^{-11}	11.9	23.0	8.2
MIR-45	9960	2.32	4.23×10^{-5}	1.70×10^{-8}	0.0	1.37×10^{-9}	27.0	8.3	9.4
MIR-48	7554	5.14	1.71×10^{-3}	21.4×10^{-2}	2.23×10^{-7}	2.38×10^{-9}	280	45.9	0.49
MIR-50	4643	5.97	7.67×10^{-2}	40.8	3.82×10^{-4}	2.08×10^{-8}	196.7	44.4	0.1
MIR-54	4290	1.50	2.46×10^{-2}	9.3	7.13×10^{-5}	2.98×10^{-6}	33.4	19.6	0.17
MIR-55	4989	3.07	7.86×10^{-4}	1.44×10^{-3}	1.97×10^{-9}	1.14×10^{-9}	14.4	52.3	0.91
MIR-59	5218	4.27	9.99×10^{-3}	7.37×10^{-3}	2.95×10^{-7}	2.00×10^{-8}	60.5	87.4	0.53
MIR-82	11320	2.77	5.85×10^{-5}	1.18×10^{-6}	0.0	1.40×10^{-10}	57.2	21.0	4.8
MIR-86	4594	1.55	8.18×10^{-4}	3.63×10^{-7}	0.0	4.50×10^{-10}	2.59	9.7	1.8