A MULTIWAVELENGTH STUDY OF THE MASSIVE STAR-FORMING REGION S87

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ABSTRACT

This article presents a multiwavelength study toward S87, based on a data set of submillimeter/far-infrared/mid-infrared (submillimeter/FIR/MIR) images and molecular line maps. The submillimeter continuum emission measured with JCMT SCUBA reveals three individual clumps, namely, SMM 1, SMM 2, and SMM 3. The MIR/FIR images obtained by the Spitzer Space Telescope indicate that both SMM 1 and SMM 3 harbor point sources. The \( J = 1-0 \) transitions of CO, \(^{13}\)CO, C\(^{18}\)O, and HCO\(^+\), measured with the 13.7 m telescope of the Purple Mountain Observatory, exhibit asymmetric line profiles. Our analysis of spectral energy distributions (SEDs) shows that all three of the submillimeter clumps are massive (110–210 \( M_\odot \)), with average dust temperatures in the range \( \sim20–40 \) K. A multiwavelength comparison convinces us that the asymmetric profiles of molecular lines should result from two clouds at slightly different velocities, and it further confirms that the star-forming activity in SMM 1 is stimulated by a cloud-cloud collision. The stellar contents and SEDs suggest that SMM 1 and SMM 3 are high-mass and intermediate-mass star-forming sites, respectively. However, SMM 2 has no counterpart below 70 \( \mu m \), which is likely to be a cold high-mass starless core. These results, as mentioned above, expose multiple phases of star formation in S87.

Subject headings: infrared: ISM — ISM: individual (S87) — ISM: molecules — stars: formation — submillimeter

1. INTRODUCTION

Massive stars play an important role in the evolution of the interstellar medium (ISM) and galaxies; nevertheless, their formation process is still poorly understood from an observational perspective because of their relatively short evolution periods, complex ambient circumstances, and gregarious nature. Two important approaches are systematic surveys and multiwavelength studies toward individual sources, which increase our knowledge about high-mass molecular cores that may harbor massive stars or mark the sites of future massive star formation. Previous surveys of high-mass star-forming regions focused on the sources associated with ultracompact (UC) \( \text{H II} \) regions and their precursors (PUCHs; Churchwell 2002). These works identified a number of high-mass protostellar objects (HMPOs; Molinari et al. 1996, 2002; Sridharan et al. 2002; Beuther et al. 2002; Wu et al. 2006). However, the identified objects usually have high luminosities (\( L_{\text{IR}} > 10^4 \ L_\odot \)), indicating that most of them do not represent the earliest stage of massive star formation. By comparing millimeter and mid-infrared (MIR) images of fields containing candidate HMPOs, Sridharan et al. (2005) further identified a sample of potential high-mass starless cores (HMSCs) that may be the sites of future massive star formation. However, their MIR identification based on 8.3 \( \mu m \) images from the Midcourse Space Experiment (MSX) was not sufficient to validate a genuine HMSC, because a heating accreting protostar may remain undetected up to 8 \( \mu m \) (Beuther & Steinacker 2007). The recently released high-resolution sensitive MIR and far-infrared (FIR) images obtained by the Galactic survey of the Spitzer Space Telescope could be used to verify these HMSC candidates.

At the same time, some works toward individual sources indicated that massive cores at early stages might exist in the vicinity of evolved star-forming sites such as UC \( \text{H II} \) or \( \text{H II} \) regions (Forbrich et al. 2004; Garay et al. 2004; Wu et al. 2005).

These works suggest that previously identified evolved sources may harbor objects at various evolutionary phases, including HMSCs, high-mass cores harboring accreting protostars, and HMPOs (Beuther et al. 2007). One scenario is that the early-stage objects are stimulated by the star-forming activities in evolved regions. Another hypothesis is that they may form with their evolved companions during the fragmentation of parent clouds, but are restrained from giving birth to stars in time by some physical supporting mechanisms. The third possible explanation is that the detected objects are just diffuse quiescent gas/dust clumps and will not ever form stars. Probing the physical properties and circumstances of these objects may help to address the questions above.

S87, cataloged as an optical \( \text{H II} \) nebula by Sharpless (1959), is a complex star-forming region at a distance of \( \sim2.3 \) kpc (Racine 1968; Crampton et al. 1978). It is associated with a bright FIR source, IRAS 19442+2427, and has been studied by a number of authors. Henkel et al. (1986) detected two 22 GHz water masers in S87. Barsony (1989) studied it at radio, infrared, and optical wavelengths, and suggested the existence of a biconical outflow. A compact \( \text{H II} \) region was detected in centimeter radio continuum, with an extended emission component (Bally & Predmore 1983; Barsony 1989). Two near-infrared (NIR) clusters were identified by Chen et al. (2003) and labeled S87E and S87W. The submillimeter continuum emission of S87 exhibited an asymmetric spatial configuration (Jenness et al. 1995; Hunter et al. 2000; Mueller et al. 2002), which was also confirmed by the molecular line map of CS \( J = 5–4 \) (Shirley et al. 2003). Previous work in ammonia (\( \text{NH}_3 \)) lines (Zinchenko et al. 1997; Stutzki et al. 1984) exposed two kinematically separate components, which spatially overlap in the direction of S87E. The recent work of Saito et al. (2007) identified several gas clumps in the C\(^{18}\)O \( J = 1–0 \) map and proposed that S87E was formed by a cloud-cloud collision. All of the works mentioned above suggest that complex spatial and kinematic structures exist in S87, which may harbor objects at different evolutionary phases. The abundant data currently available from various wavelengths give us a great opportunity to perform a further comprehensive investigation toward S87. This may
2. DATA AND OBSERVATIONS

2.1. Continuum Data

All of the submillimeter/FIR/MIR continuum maps or images of S87 were obtained from data archives. The 850 and 450 μm submillimeter continuum data were retrieved from the James Clerk Maxwell Telescope4 (JCMT) Science Archive, measured with the Submillimetre Common-User Bolometer Array (SCUBA; Holland et al. 1999) installed at JCMT. Two 850 and 450 μm maps are available because S87 was observed twice in 2003. One observation was carried out in jiggle map mode on 2003 May 24 (JCMT program ID M03AN23); the other was performed in Ellison II scan mode on August 24 (M03BU45). The beamwidths of JCMT were 7.5'' (450 μm) and 14'' (850 μm). All of the retrieved data have been fully calibrated with the ORAC-DR pipeline (Jenness et al. 2002) for flat-fielding, extinction correction, sky noise removal, despiking, and removal of bad pixels, in units of mJy beam$^{-1}$. The Spitzer MIR/FIR data were retrieved from Spitzer Science Center, including the 3.6, 4.5, 5.8, and 8.0 μm images measured with the Infrared Array Camera (IRAC; Fazio et al. 2004) and the 24 and 70 μm images measured with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). The IRAC and MIPS data are, respectively, from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003) and the recently released MIPS Inner Galactic Plane Survey (MIPSGAL; Carey et al. 2005). All of them were calibrated by the Spitzer Science Center data processing pipelines. In addition, we also retrieved the MIR images and point source catalog (PSC) of MSX (Egan et al. 2003) from the Infrared Processing and Analysis Center (IPAC)$^5$ for our study.

2.2. Spectral Observation

To investigate the molecular gas of S87, we mapped a region $4' \times 4'$, centered on IRAS 19442+2427 in the $J = 1-0$ transitions of CO, $^{13}$CO, C$^{18}$O and HCO$^+$, with the 13.7 m millimeter telescope of Purple Mountain Observatory (PMO) in 2005 January and 2006 May. A cooled SIS receiver was employed, and the system temperature, $T_{sys}$, at the zenith was $\sim$250 K (SSB). The back end included three acousto-optical spectrometers, which were able to measure the $J = 1-0$ transitions of CO, $^{13}$CO, and C$^{18}$O simultaneously. All the observations were performed in position switch mode. The center reference coordinates are R.A. ($J2000.0$) = 19$^h$46$^m$19.9$^s$, decl. ($J2000.0$) = +24$^\circ$35'24''. The grid spacings of the CO and HCO$^+$ mapping observations were 60$''$ and 30$''$, respectively. The background positions were checked by single point observations before mapping. The pointing and tracking accuracy was better than 10$''$. The obtained spectra were calibrated in the scale of antenna temperature $T_A^*$. The grid spacings of the CO and HCO$^+$ mapping observations were 60$''$ and 30$''$, respectively. The background positions were checked by single point observations before mapping. The pointing and tracking accuracy was better than 10$''$. The obtained spectra were calibrated in the scale of antenna temperature $T_A^*$. The grid spacings of the CO and HCO$^+$ mapping observations were 60$''$ and 30$''$, respectively. The background positions were checked by single point observations before mapping. The pointing and tracking accuracy was better than 10$''$. The obtained spectra were calibrated in the scale of antenna temperature $T_A^*$. The grid spacings of the CO and HCO$^+$ mapping observations were 60$''$ and 30$''$, respectively. The background positions were checked by single point observations before mapping. The pointing and tracking accuracy was better than 10$''$. The obtained spectra were calibrated in the scale of antenna temperature $T_A^*$.

Table 1 summarizes the basic information about our observations, including the transitions, the center rest frequencies $v_{rest}$, the half-power beam widths (HPBWs), the bandwidths, the equivalent velocity resolutions ($\Delta v_{res}$), and the typical rms levels of measured spectra. All spectral data were transformed from $T_A^*$ to $T_R$ scale with the main beam efficiencies before analysis. The uncertainty of brightness was estimated to be 10%. The GILDAS$^6$ software package (CLASS/GREG) was used for data reduction (Guilloteau & Lucas 2000).

2.3. Other Archival Data

We acquired the 350 μm continuum and NH$_3$ ($J, K$) = (1, 1) line maps of S87 through private communications with K. Young and I. Zinchenko in 2006. The 350 μm map was measured with the Submillimeter High Angular Resolution Camera (SHARC) installed at the Caltech Submillimeter Observatory (CSO; Mueller et al. 2002). The NH$_3$ ($J, K$) = (1, 1) line map was obtained with the Effelsberg 100 m telescope (Zinchenko et al. 1997). The technical details are summarized in the corresponding reference articles.

3. RESULTS

3.1. Submillimeter Maps

Figure 1 displays the 850 μm scan map (contours) and the Spitzer 8.0 μm image (inverse gray scale), in which the NIR clusters S87E and S87W are revealed as two bright MIR nebulae. The strongest peak of 850 μm is associated with S87E, and two other peaks exist to the northeast of it. We propose that these three 850 μm peaks are associated with three individual

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*Typical value in the scale of $T_A^*$.  
$^4$ See http://ssc.spitzer.caltech.edu. 
$^5$ See http://www.ipac.caltech.edu.

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### TABLE 1 
**Observation Parameters**

| Transition   | $v_{rest}$ (GHz) | HPBW (arcsec) | Bandwidth (MHz) | $\Delta v_{res}$ (km s$^{-1}$) | 1 σ rms$^a$ (K chan.$^{-1}$) |
|--------------|------------------|---------------|-----------------|------------------------------|-----------------------------|
| CO $J = 1-0$ | 115.271204       | 46            | 145             | 0.37                         | 0.18                        |
| $^{13}$CO $J = 1-0$ | 110.201353       | 47            | 43              | 0.11                         | 0.14                        |
| C$^{18}$O $J = 1-0$ | 109.782182       | 48            | 43              | 0.12                         | 0.14                        |
| HCO$^+$ $J = 1-0$ | 89.188521        | 58            | 43              | 0.26                         | 0.11                        |

$a$ Typical value in the scale of $T_A^*$. 

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3 The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

4 See http://ssc.spitzer.caltech.edu.

5 See http://www.ipac.caltech.edu.

6 See http://www.iram.fr/IRAMFR/GILDAS.
submillimeter clumps. They lie along an axis from southwest to northeast, and are hereafter labeled SMM 1, SMM 2, and SMM 3. We processed the submillimeter maps using the Richardson-Lucy (RL) iteration deconvolution algorithm to moderately enhance the spatial resolutions. Like many other deconvolution solutions, this algorithm did not produce uncertainty information for the results. Therefore, we have to note that this process is not targeted to get the most “accurate” deconvolved maps. Our steps of deconvolution are similar to those described by Smith et al. (2000). The 850 and 450 $\mu$m maps of SCUBA were constructed from the Uranus maps measured in 2003 August. A procedure in Starlink KAPPA was used to perform the image processing tasks. We avoided the pixels at the edge of the submillimeter maps during the iterations due to their low signal-to-noise level.

The deconvolutions of the two 850 $\mu$m maps converged within 100 iterations and produced acceptable enhanced images without apparently artificial structures. However, for the 450 $\mu$m maps, the procedure failed to converge within 150 iterations. Figure 2 displays the deconvolved 850 $\mu$m maps and undeconvolved 450 $\mu$m maps. All of them have been converted into mJy arcsec$^{-2}$. SMM 3 is not covered in the jiggle maps (see Figs. 2c and 2d) due to the limitation of the observational fields of view. SMM 1 is clearly elongated in the deconvolved 850 $\mu$m maps, and there are extended lobes to the west and south of its peak. SMM 2 is slightly elongated in the north-south direction. All of the three submillimeter clumps are revealed in a common envelope, suggesting that they may be associated although not necessarily in the same sky plane.

To evaluate the CO $J = 3$–2 contribution to the 850 $\mu$m data, we examined our previous observation of S87 in CO $J = 3$–2 at the Kölner Observatory for Submillimeter Astronomy (KOSMA) 3 m telescope. This observation was carried out for a CO multiline survey of (UC) H ii regions and has not been published yet (R. Xue & Y. Wu 2008, in preparation). After converting the integrated intensity of CO $J = 3$–2 to a flux density at 850 $\mu$m, we found that the contribution of CO $J = 3$–2 is less than the noise level of the 850 $\mu$m maps. We also evaluated the contribution of CO $J = 6$–5 to the 450 $\mu$m data by estimating its integrated intensity from CO $J = 3$–2, under the assumption of local thermodynamic equilibrium (LTE) with an excitation temperature of 80 K. We found that its contribution is also small. Therefore, the effect of line contaminations can be ignored at 450 and 850 $\mu$m.

3.2. Mid-/Far-Infrared Images

A luminous MIR point source is revealed at the position of the compact H ii region (see the IRAC images of Figs. 1 and 3),

![Fig. 1.—JCMT SCUBA 850 $\mu$m continuum emission (contours) overlaid on the Spitzer IRAC 8.0 $\mu$m image. The contour levels increase from 0.6 to 5.0 Jy beam$^{-1}$, in steps of 0.4 Jy beam$^{-1}$ (4 $\sigma$). The inverse gray-scale 8.0 $\mu$m image is in the unit of MJy sr$^{-1}$. The coordinate system is J2000.0. The two small open circles mark the water masers detected by Henkel et al. (1986). The square denotes the compact H ii region, and the open ellipse indicates the position and rough size of the associated extended centimeter emission (Barsony 1989). The open circle at the bottom shows the beamwidth of JCMT at 850 $\mu$m. The submillimeter clumps SMM 1, SMM 2, and SMM 3, as well as the NIR clusters S87E and S87W, are labeled. Three 8.0 $\mu$m point sources, named MIRS 1, MIRS 2, and MIRS 3 in § 3.2, are marked by arrows.](http://www.jach.hawaii.edu/software/starlink)
which we henceforth label MIRS 1. A weaker MIR point source is found in the 3.6, 4.5, and 5.8 \(\mu m\) images, \(~8^\circ\) to the southwest of MIRS 1. It is also detected by the 2MASS NIR All-Sky Survey and cataloged as 2MASS 19461947+2435247. However, we did not find the NIR counterpart of MIRS 1 in 2MASS images, indicating that MIRS 1 is highly obscured by the surrounding gas/dust envelope at NIR wavelengths. In the zoomed-in 8 \(\mu m\) image of Figure 1, two other point sources are found to the north of MIRS 1; we label these MIRS 2 and MIRS 3. Strong diffuse MIR emission exists to the southeast of MIRS 1, coincident with the extended centimeter emission detected by Barsony (1989). Faint diffuse MIR emission is detected in the northeast of the IRAC images, coincident with SMM 3. SMM 2 has no NIR counterpart in all of the IRAC bands.

S87E and S87W saturate the 24 and 70 \(\mu m\) MIPS images. Five other sources are detected in the 24 \(\mu m\) band, which are coincident with the diffuse MIR emission in the IRAC bands. We label them MIRS 4–MIRS 8 (see Fig. 3). Although the 24 and 70 \(\mu m\) images are saturated toward SMM 1, it is still clear that the peaks of submillimeter and 24 \(\mu m\) emission are separate, which is also confirmed by a comparison with the MSX E band (21.3 \(\mu m\)) image. SMM 3 is associated with MIRS 4. However, its submillimeter peak and MIRS 4 are also slightly separated. There are only weak emission patches in the IRAC 5.8 and 8.0 \(\mu m\) bands toward SMM 3, indicating that MIRS 4 is still

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**Fig. 2.**—Contour plots of the submillimeter continuum maps, overlaid on their inverse gray-scale images. The beamwidth is indicated in the bottom right corner of each panel. (a) Deconvolved 850 \(\mu m\) scan map (M03BU45), after 98 iterations. The three open circles over the emission peaks denote the photometric apertures (see § 4). (b) Deconvolved 450 \(\mu m\) scan map (M03BU45). The contours are 40, 120, 220, and 380 mJ arcsec\(^{-2}\). (c) Deconvolved 850 \(\mu m\) jiggle map (M03AN23), after 51 iterations. The contours increase from 2 to 26 mJ arcsec\(^{-2}\) in steps of 3 mJ arcsec\(^{-2}\). (d) Deconvolved 450 \(\mu m\) jiggle map (M03AN23). The contours are 60, 120, 200, 280, 360, 440, and 500 mJ arcsec\(^{-2}\).

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**Fig. 3.**—Spitzer MIR/FIR images at six wavelengths. The sizes and positions of the six panels are the same. The absolute coordinates (J2000.0) are exhibited in the 8.0 \(\mu m\) panel. The white areas in the emission regions of the 24 and 70 \(\mu m\) images are due to the saturation of the detectors. The MIR emission is also plotted as contours in the 3.6, 4.5, 5.8, and 8.0 \(\mu m\) panels. Their contour levels are 1%, 2%, 3%, 5%, 10%, 16%, 28%, 50%, and 90% of the peak intensities. The plus signs in each panel denote the 850 \(\mu m\) peaks. The square indicates the compact H II region. The contour plot of the 24 \(\mu m\) panel is the 850 \(\mu m\) continuum emission, adopted from Fig. 2a. MIRS 4–MIRS 8 are also marked in the 24 \(\mu m\) panel. The small open circles in the bottom right corner of the 24 and 70 \(\mu m\) panels denote the resolutions of these observations.

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8 The recently released GLIMPSE Spring '05 Catalog names it SSTGLMC G60.8838-0.1292.
embedded in its gas/dust cocoon. No 24 or 70 μm emission is detected toward SMM 2, suggesting that it may be less evolved.

3.3. Molecular Lines

The \( J = 1 \rightarrow 0 \) transitions of CO, \(^{13}\)CO, and HCO\(^+\) exhibit asymmetric line profiles (see Fig. 4, left), and two components are detected in \(^{13}\)CO \( J = 1 \rightarrow 0 \). Since \(^{13}\)CO \( J = 1 \rightarrow 0 \) is usually optically thin, we can rule out the possibility that the asymmetric line profile in the other transitions is caused by self-absorption in an infall envelope (Myers et al. 1996; Wu et al. 2005). Previous observations of Stutzki et al. (1984) and Zinchenko et al. (1997) also detected two separate components in NH\(_3\) (\( J, K \)) = (1, 1) and NH\(_3\) (\( J, K \)) = (2, 2) lines. The NH\(_3\) (\( J, K \)) = (1, 1) spectra of Zinchenko et al. (1997) and our \(^{13}\)CO \( J = 1 \rightarrow 0 \) spectra at several positions are plotted in the right panel of Figure 4. These spectra further confirm that the broad lines of CO \( J = 1 \rightarrow 0 \), \(^{13}\)CO \( J = 1 \rightarrow 0 \), and HCO\(^+\) \( J = 1 \rightarrow 0 \) consist of two components.

We fitted our spectra at the reference position with Gaussian profiles. The results are displayed as thin lines in Figure 4, and the corresponding derived parameters are summarized in Table 2, including the line center velocities, the fitted line widths, and the brightness temperatures. We estimated the beam-averaged column densities of \(^{13}\)CO at the reference position using the standard LTE method. The excitation temperature of each component is assumed to be 35 K, in agreement with the estimation from CO \( J = 1 \rightarrow 0 \) (assuming it is optically thick). The derived \(^{13}\)CO column densities are \( \sim 7.8 \times 10^{15} \) and \( 4.0 \times 10^{15} \) cm\(^{-2}\) for the components at low and high velocities.

Figure 5a is the HCO\(^+\) \( J = 1 \rightarrow 0 \) position-velocity diagram along the northeast-southwest direction, which also exhibits two components. One is located at the reference position and is associated with SMM 1; the other extends from the reference position to the northeast, coincident with SMM 2 and SMM 3. We propose that these components arise from two clouds. Hereafter, the parameters of molecular lines are listed in Table 2.

### Table 2

| Transition \(^{13}\)CO \( J = 1 \rightarrow 0 \) | \( V_{LSR} \) \( (\text{km s}^{-1}) \) | \( \Delta V \) \( (\text{km s}^{-1}) \) | \( T_R \) \( (\text{K}) \) |
|-----------------|-----------------|-----------------|-----------------|
| \(^{13}\)CO \( J = 1 \rightarrow 0 \) | 21.51 (0.08) | 1.93 (0.04) | 16.71 (0.38) |
| \(^{13}\)CO \( J = 1 \rightarrow 0 \) | 21.48 (0.08) | 1.69 (0.19) | 2.39 (0.39) |
| \(^{13}\)CO \( J = 1 \rightarrow 0 \) | 23.61 (0.04) | 2.60 (0.06) | 15.04 (0.38) |
| \(^{13}\)CO \( J = 1 \rightarrow 0 \) | 23.78 (0.16) | 1.83 (0.42) | 1.14 (0.39) |
| HCO\(^+\) \( J = 1 \rightarrow 0 \) | 22.30 (0.04) | 3.10 (0.16) | 4.54 (0.11) |

Note.—The error levels are from Gaussian fitting.

* The superscripts indicate the different components.

* Since the two components cannot be well resolved, the derived parameters are from single Gaussian fitting.
they are named Clouds I and II, corresponding with the components at low and high velocity, respectively.

The integrated intensity maps of HCO\(^+\) \(J = 1-0\) and NH\(_3\) \((J, K) = (1, 1)\) are also exhibited in Figure 5. Two different integrated intervals are adopted, chosen to separate the emission from Clouds I and II. All of the presented intensity maps suggest that SMM 2, SMM 3, and the northeast part of SMM 1 may be associated with Cloud II; the main part of SMM 1 is contributed by Cloud I.

4. SED ANALYSIS

4.1. Observational SEDs

We extracted the 850 and 450 \(\mu m\) flux densities of each clump using a photometric procedure in the Starlink GAIA (Graphical Astronomy and Image Analysis Tool) software package. The measured results, as well as the positions and sizes of the adopted photometric apertures, are summarized in Table 3. We note that the uncertainties in Table 3 are just statistical errors (rms deviations derived from clean regions), and the estimation of the overall photometric uncertainties is difficult due to the limited information from the online data archives. However, a comparison among different observational modes and the previous similar observation may provide an evaluation of the accuracy of our results.

Jenness et al. (1995) observed S87 using the receiver UKT14 at JCMT in 1994. They detected two sources, which were coincident with SMM 1 and SMM 2, respectively. Our photometric results at 850 \(\mu m\) are in good agreement with theirs (see the last two columns of Table 3), but the 450 \(\mu m\) results from SCUBA are systematically larger. Since UKT14 is a single-element bolometer and its measurements may be affected by the change of sky conditions and other factors, we believe that the calibration of SCUBA data is more reliable. The photometric differences of the jiggle and scan maps are acceptable, less than 20% at 450 \(\mu m\).

We examined the CSO map and the MIPS images to measure the flux densities of each clump at 24, 70, and 350 \(\mu m\). Since SMM 1 saturates the 24 and 70 \(\mu m\) images, only lower limits can be derived at these wavelengths. In addition, we checked the MSX PSC and found that the photometric apertures of SMM 1 and SMM 3 are coincident with the MSX point sources MSX6C G060.8828-0.1295 and MSX6C G060.9049-0.1275, respectively. Their flux densities are also adopted to construct the SEDs of SMM 1 and SMM 3.

The measured flux densities are summarized in Table 4, extending from submillimeter to MIR. The average results of the scan and jiggle maps are adopted for 850 and 450 \(\mu m\). Their differences are considered as the uncertainties. The 350 \(\mu m\) uncertainties follow the description of Mueller et al. (2002) and the uncertainties at 24 and 70 \(\mu m\) are the statistical errors.

4.2. Isothermal Dust Model

A simple isothermal gray-body dust model is used to fit the observational SEDs. The details follow the method described by

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**TABLE 3**

| Object | \(\alpha\) (J2000.0) | \(\delta\) (J2000.0) | \(\theta_p\) (arcsec) | 850 \(\mu m^a\) (Jy) | 450 \(\mu m^a\) (Jy) | 850 \(\mu m^b\) (Jy) | 450 \(\mu m^b\) (Jy) | 850 \(\mu m^c\) (Jy) | 450 \(\mu m^c\) (Jy) |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SMM 1  | 19 46 19.8      | +24 35 32       | 60              | 17.7 ± 0.1      | 133 ± 10        | 16.8 ± 0.1      | 167 ± 1         | 17              | 110             |
| SMM 2  | 19 46 22.3      | +24 36 01       | 30              | 5.8 ± 0.1       | 32 ± 6          | 5.3 ± 0.1       | 45 ± 1          | 6.5             | 18              |
| SMM 3  | 19 46 23.2      | +24 36 28       | 30              | 4.1 ± 0.1       | 25 ± 6          | ...             | ...             | ...             | ...             |

* Flux densities extracted from the scan map (M03BU45).
* Flux densities extracted from the jiggle map (M03AN23).
* Flux densities from Jenness et al. (1995).
We further calculated their clump masses and bolometric luminosities. We adopted the dust opacity indices of Msx PSC. We assumed the average dust temperature to be 150 K, and the aperture-averaged column density of hydrogen molecules \( N_H \) to be 1.3 \( \times \) 10\(^{22} \) cm\(^{-2} \). In this fitting test, the only data above 70 \( \mu m \) were used. We assumed the 70 \( \mu m \) flux density of SMM 1 to be 4000 Jy, which was estimated from the extrapolation of the Spitzer 24 and 70 \( \mu m \) images. We assumed the 70 \( \mu m \) flux density of SMM 1 to be 4000 \( \pm 200 \) Jy when performing the SED fitting.

SMM 2 and SMM 3 are not detected in any of the four MSX bands. The open triangles denote the flux densities extracted from MSX PSC. The open squares indicate the flux densities derived from the Spitzer MIPS images. The small filled squares on the model SEDs are the data points used for the SED fitting. The error bar of each data point is plotted if available.

The results in Table 5 show that the submillimeter clumps are all massive \((110^{–}220 M_\odot)\). SMM 1 has a higher dust temperature, and its bolometric luminosity dominates in the whole region, implying the existence of a strong internal heating source(s). The fitted dust opacity indices of three submillimeter clumps are slightly different \((\sim 1.3^{–}1.8)\) and consistent with the typical values between 1 and 2 \( (\text{Hill et al. 2006}) \). It must be noted that the derived \( N_H \) is directly affected by the adopted value of \( \kappa_{1300} \). If we reduce \( \kappa_{1300} \) by a factor of 2, \( N_H \), and the derived clump mass \( M \) will increase by a factor of 2. However, the other derived parameters will not be affected by this change.

### 4.3. Two-Temperature Dust Model

In Figure 6, the best-fit models of SMM 1 and SMM 3 failed to describe the observational results below 70 \( \mu m \). However, the model SED of SMM 2 can explain the absence of its MIR emission. To better characterize the excess MIR emission of SMM 1 and SMM 3, we performed another SED fitting test using a model with two dust components at different temperatures. In this fitting test, we adopted the observational data above 14.7 \( \mu m \) \((24 \mu m \text{ for SMM 1})\). To reduce the fitting parameters, we assumed that \( \beta = 1.5 \) and 1.3 for each dust component of SMM 1 and SMM 3, respectively. The best-fit model SEDs are exhibited in Figure 7, and the derived parameters of the warm and cool dust components are listed in Table 6.

The two-temperature model fits the observational data very well above 12 \( \mu m \), which is consistent with the physical fact that there is warm dust around the internal heating sources and relatively cool dust envelopes surrounding the star-forming sites in SMM 1 and SMM 3. Although the IRAS 100 \( \mu m \) flux density exceeds the model SED of SMM 1 \( \text{(see Fig. 7)} \), we believe that

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### Table 4

**Flux Densities of the Submillimeter Clumps**

| Object     | 850 \( \mu m \) (Jy) | 450 \( \mu m \) (Jy) | 350 \( \mu m \) (Jy) | 70 \( \mu m \) (Jy) | 24 \( \mu m \) (Jy) | 21.3 \( \mu m^2 \) (Jy) | 14.7 \( \mu m^2 \) (Jy) | 12.1 \( \mu m^2 \) (Jy) | 8.3 \( \mu m^2 \) (Jy) |
|------------|----------------------|---------------------|--------------------|-------------------|-----------------|-----------------------|----------------------|-------------------------|----------------------|
| SMM 1      | 17.3 ± 0.9           | 150 ± 34            | 256 ± 46           | >1500             | >24             | 225 ± 13              | 43.3 ± 2.3           | 31.7 ± 1.6              | 19.6 ± 0.8            |
| SMM 2      | 5.5 ± 0.6            | 39 ± 13             | 79 ± 14            | 49 ± 3            | <3              | ...                   | ...                  | ...                     | ...                  |
| SMM 3      | 4.1 ± 0.6            | 25 ± 6              | 40 ± 8             | 36 ± 3            | 9.1 ± 3         | 5.1 ± 0.4             | 0.6 ± 0.1            | 1.1 ± 0.1               | 1.3 ± 0.1             |

* These values are derived from MSX PSC. We adopted the dust densities of MSX C G060.8828-00.1295 and MSX C G060.9049-00.1275 for SMM 1 and SMM 3, respectively. SMM 2 is not detected in any of the four MSX bands.

\( ^b \) Only the lower limits are available due to the saturation of the Spitzer 24 and 70 \( \mu m \) images.

\( ^c \) No detection.
the deviation is due to the large beam of IRAS. The results in Figure 7 and Table 6 show that the warm components contribute little to the total masses and the flux densities at submillimeter wavelengths, but are required to explain the excess at MIR wavelengths. We tried to modify $\beta$ to fit the emission below 12 $\mu$m. However, no satisfying results were found. The emission in the MSX A and C bands does not follow the prediction of gray-body models, suggesting these models are invalid at these wavelengths. Generally, two significant spectral features may exist at this MIR wavelength range. One is the emission of polycyclic aromatic hydrocarbons (PAHs), which is often detected toward compact H II regions and photodissociation regions (PDRs). Previous studies have shown that the MSX A and C bands often contain PAH emission lines (Ghosh & Ojha 2002; Kraemer et al. 2003a, 2003b; Povich et al. 2007). The other is the silicate feature, which has been predicted in the dust model of Ossenkopf & Henning (1994) and demonstrated to be important in recent sophisticated SED models (Robitaille et al. 2006, 2007). This feature may be expected as the absorption at 9.7 $\mu$m toward some UC H II regions, produced by the dust cocoons around center objects (Faison et al. 1998). Peeters et al. (2002) have identified both of PAH and silicate features toward S87E in the previous ISO spectroscopy observation. The silicate absorption feature may be caused by Cloud II, which partly overlaps above the compact H II region. Since our gray-body models are focused to evaluate the overall properties of dust clumps, which are mainly constrained by the thermal emission from longer wavelengths, a detailed SED model explaining the PAH and silicate features is beyond our purpose.

5. DISCUSSION

5.1. Cloud-Cloud Collision

All of the FIR/submillimeter images and molecular line maps exhibit the complex spatial and kinematical structures of S87. Recently published high-resolution C$^{18}$O $J = 1$–$0$ observations (Saito et al. 2007) revealed several gas clumps at different velocities, which further confirms our identification of Clouds I and II. However, are Clouds I and II really related to each other? Saito et al. (2007) proposed that the gas clumps at higher velocity might be on the near side along the line of sight because the observation of Chen et al. (2003) detected many reddened sources in NIR there. They further reasoned that the clumps at low and high velocities were approaching and the NIR cluster S87E was possibly formed by a cloud-cloud collision. In the following, we verify the cloud-cloud collision model by a multiwavelength comparison. First, the 8.0 $\mu$m emission shows a sharp edge to the northeast of MIRS 1 (see Fig. 1). This feature is probably caused by the large extinction at 8.0 $\mu$m because the submillimeter emission is still strong. The position of the extinction patch is consistent with that of Cloud II, confirming that Cloud II is on the near side along the line of sight. Therefore, Clouds I and II are approaching.

Next, we can infer from the intensity maps of Figure 5 that the peaks of SMM 1 and S87E are in the overlapping region of Clouds I and II. The NIR point sources in SMM 1 suggest that there is not only an existing NIR cluster, but also ongoing star-forming activities. The strong and continuous star-forming process is likely to be interpreted by the stimulation of a cloud-cloud collision rather than the spontaneous evolution of molecular clouds alone.
Furthermore, the spatial configuration of the compact H II region and the associated extended centimeter emission (Barsony 1989; Kurtz et al. 1994) also supports the cloud-cloud collision model. The champagne flow model of Kim & Koo (2001) combined with the clumpy structures of molecular clouds can explain the extended centimeter component that stretches to the southeast of the compact H II region. If Clouds I and II are in contact, their contact plane will be along the northwest-southeast direction (see Figs. 5b and 5c). Consequently, the compact H II region will be better confined in the direction perpendicular to the contact plane and it should be easier for the champagne flow to spurt out in the southeast direction. If Clouds I and II are not in contact, the champagne flow will be more likely to splash in the direction perpendicular to the border of the parent cloud of the compact H II region. The observational result is consistent with the prediction of the first scenario, supporting the idea that the two clouds are colliding. Assuming that the two clouds have typical sizes $R \sim 1$ pc and a velocity separation $\Delta v \sim 2$ km s$^{-1}$, the collision duration is at least $R/\Delta v \sim 5 \times 10^5$ yr, comparable with the timescale forming a compact H II region.

The cloud-cloud collision is considered an efficient mechanism to trigger star formation. It may compress molecular gas and lead to local gravitational collapse (Loren 1976; Habe & Ohta 1992; Marinho et al. 2001). However, its possibility is small in the diffuse molecular clouds (Elmegreen 1998). In addition, high-velocity off-axis collisions could be destructive rather than leading to gravitational instabilities (Hausman 1981; Gilden 1984). Therefore, the fraction of star formation triggered by cloud-cloud collisions may be small in our Galaxy. All of the current evidence demonstrates that S87 is a new example of cloud-cloud collision, and similar samples are still limited (Loren 1976; Dickel et al. 1978; Koo et al. 1994; Vallee 1995; Buckley & Ward-Thompson 1996; Sato et al. 2000; Looney et al. 2006).

5.2. Molecular Line Emission

5.2.1. HCO$^+$ J = 1–0

Our observation shows that the line profile of HCO$^+$ J = 1–0 is similar to that of CO J = 1–0 (see Fig. 4, left). In addition, we found that both CO J = 1–0 and HCO$^+$ J = 1–0 spectra show slight features of high-velocity (HV) gas when compared with C$^{18}$O J = 1–0, suggesting that HCO$^+$ extends in diffuse gas rather than simply being concentrated in the dense parts of gas clumps. Previous observational and theoretical works have pointed out the abundance enhancement of HCO$^+$ in diffuse or shocked gas (Turner 1995b; Girart et al. 1999), which can explain our finding.

However, the formation mechanism of the HV gas in S87 is unclear. We propose three different explanations: (1) the HV gas may arise from stellar outflows; (2) it may be contributed by the high-pressure shocked material that is squirited out when the clouds collide; or (3) it is from the nonimpacting portions of the colliding clouds since they do not slow down to a common speed during the cloud-cloud collision. Although Barsony (1989) identified HV blue and red wings in her CO J = 1–0 observation and proposed that the HV gas resulted from a biconical outflow with a wide opening angle viewed at large inclination, our identification of two individual clouds apparently rejects this model. High-resolution and sensitive observations are required to clarify the origin of the HV gas.

Because both stellar outflows and cloud-cloud collisions can produce HV gas and broad non-Gaussian line profiles, it is possible that some observational results previously interpreted as bipolar outflows are caused by cloud-cloud collisions. However, since the possibility of cloud-cloud collisions is not high, similar cases like S87 should be rare.

5.2.2. NH$_3$ (J, K) = (1, 1)

A feature of the NH$_3$ (J, K) = (1, 1) intensity maps is that the NH$_3$ emission tends to “evade” the luminous MIR sources. The NH$_3$ (J, K) = (1, 1) peak of Cloud I is separate from MIRS 1 and the submillimeter peak of SMM 1. The NH$_3$ (J, K) = (1, 1) emission is absent to the southeast of MIRS 1, where the diffuse MIR emission is strong. The NH$_3$ (J, K) = (1, 1) peak of Cloud II is coincident with SMM 2, which has no MIR counterpart. In contrast, the observations of Saito et al. (2007) and Shirley et al. (2003) showed that the C$^{18}$O J = 1–0 and CS J = 5–4 emission is strong in SMM 1 and SMM 3. Since both SMM 1 and SMM 3 are dense clumps identified from submillimeter continuum, their relatively weak NH$_3$ emission may be explained by the underabundance of NH$_3$. Turner (1995a) suggested that NH$_3$ could be destroyed by the C$^+$ that dominates in PDRs. However, molecules such as C$^{18}$O are formed via C$^+$ and not affected by the photodestruction process (Jansen et al. 1995). The diffuse 5.8 and 8.0 $\mu$m emission near SMM 1 and SMM 3 is usually contributed by PAHs and interpreted as a tracer of PDRs. The existence of MIR emission there, as well as the strong C$^{18}$O J = 1–0 emission and the weak NH$_3$ emission, is consistent with the prediction of the chemical process proposed in previous works.

5.2.3. Virial States

The line widths of molecular spectra are usually used to probe the kinematics of gas clumps. Since Clouds I and II can be well resolved in NH$_3$ lines, we estimate the virial masses of these two clouds in this section.

We derived the line widths and brightness temperatures of NH$_3$ (J, K) = (1, 1) at the NH$_3$ peaks of Clouds I and II, using the hyperfine structure fitting procedure of GILDAS/CLASS. The results are exhibited as thin lines in Figure 4. The angular
diameters $\theta_{\text{obs}}$ of Clouds I and II are calculated using the equation

$$\theta_{\text{obs}} = 2 \sqrt{\frac{\Omega}{\pi}},$$  \hspace{1cm} (2)

in which $\Omega$ is the measured angular area of each cloud. After that, we corrected the beam effect and estimated the intrinsic sizes of Clouds I and II following the equation

$$R = D \frac{\sqrt{\theta_{\text{obs}}^2 - \theta_{\text{mb}}^2}}{2},$$  \hspace{1cm} (3)

where $R$ is the radius of the gas cloud in pc, $D$ is the distance of S87, and $\theta_{\text{mb}}$ is the beamwidth of the NH$_3$ ($J, K = (1, 1)$) observation. Assuming that Clouds I and II are homogeneous spherical gas clouds with a density distribution $\rho \propto r^{-\alpha}$ ($\alpha = 1.5$) and neglecting the contributions from magnetic field and surface pressure, the virial masses can be derived using the equation (MacLaren et al. 1998)

$$M_{\text{vir}} = 126 \left(\frac{5 - 2\alpha}{3 - \alpha}\right) R \Delta V_{\text{FWHM}}^2,$$  \hspace{1cm} (4)

in which $M_{\text{vir}}$ is the virial mass in $M_\odot$, and $\Delta V_{\text{FWHM}}$ is the full width at half-maximum intensity (FWHM) of NH$_3$ ($J, K = (1, 1)$) in km s$^{-1}$.

All the measured and derived parameters of Clouds I and II are listed in Table 7, including the positions of NH$_3$ peaks, the angular and intrinsic sizes, the line widths at NH$_3$ peaks, and the derived virial masses of two clouds. The total virial mass of Clouds I and II is $\sim 430 M_\odot$, which is much smaller than the previous estimation ($\sim 1080 M_\odot$) obtained with the total line width of two components (Zinchenko et al. 1997) but comparable to the mass estimated from the SED fitting ($\sim 460 M_\odot$, from the isothermal dust model). However, we note that the above comparison of the masses estimated from different approaches can be affected by the adopted dust opacity and the assumption of $\alpha$. Although a variation of $\alpha$ is not likely to cause much change in virial masses, the dust opacity may change by at least a factor of 2 (Ossenkopf & Henning 1994), which leads to a large uncertainty in the masses estimated from SEDs.

### 5.3. Stellar Contents of SMM 1 and SMM 3

The position of MIRS 1 is consistent with that of the compact H II region, within the astrometric error (1.5$''$), indicating that MIRS 1 is the exciting massive (proto)star. We examined the high-resolution centimeter map of Barsony (1989) and found that neither MIRS 2 nor MIRS 3 shows compact radio continuum emission. The possible explanation is that MIRS 2 and MIRS 3 are less evolved compared with MIRS 1 or that they are not massive enough to ionize their surroundings and to excite compact H II regions. Henkel et al. (1986) detected a strong water maser in SMM 1, which is often considered to be associated with HMPOs. The velocity range of this water maser is 21–25 km s$^{-1}$, in good agreement with the systematic velocity of the molecular clouds. All the evidence mentioned above supports SMM 1 being a high-mass star-forming site that harbors massive forming stars or a cluster.

The Lyman continuum radiation from massive stars mainly escapes in the form of free-free emission. Kurtz et al. (1994) estimated that the Lyman continuum photon flux required to keep the entire region of S87E ionized was $3.2 \times 10^{46}$ photons s$^{-1}$, which corresponds to that of a B0.5 zero-age main sequence star. The bolometric luminosity of such stars is $\sim 3.0 \times 10^4 L_\odot$ (Crowther 2005), slightly smaller than that of SMM 1 ($\sim 3.7 \times 10^4 L_\odot$, from the two-component model). The extra luminosity of SMM 1 may come from the relatively weak MIR sources near MIRS 1, which cannot be traced by the free-free emission.

SMM 3 contains the bright 24 $\mu$m source MIRS 4. The ratio of the luminosities from its cool and warm components is $\sim 2.1$, lower that of SMM 1. Its bolometric luminosity is $\sim 740 L_\odot$, also lower than that of SMM 1, which indicates that SMM 3 is more likely to be an intermediate-mass star-forming site.

### 5.4. Physical Properties of SMM 2

No MIR point source or diffuse emission below 70 $\mu$m is detected toward SMM 2. Since only a cold dust component can describe its observational SED, strong internal heating sources are not likely to exist in SMM 2.

Henkel et al. (1986) detected a weak 22 GHz water maser, which usually arises from the dense circumstellar disks around protostars (Park & Choi 2007) or originates in outflows from the birth of a massive star (van Dishoeck & Blake 1998), near SMM 2. Since this water maser is in the velocity range 8–15 km s$^{-1}$, significantly different from that of the molecular clouds, we favor the second explanation for its origin. We notice that this water maser is on a submillimeter emission ridge connecting the peaks of SMM 1 and SMM 2 rather than near the peak of SMM 2, and this maser is on a submillimeter emission ridge connecting the peaks of SMM 1 and SMM 2 rather than near the peak of SMM 2, which is consistent with the second explanation for its origin. We notice that this water maser is on a submillimeter emission ridge connecting the peaks of SMM 1 and SMM 2 rather than near the peak of SMM 2, and this maser is on a submillimeter emission ridge connecting the peaks of SMM 1 and SMM 2 rather than near the peak of SMM 2, which is consistent with the second explanation for its origin.

Thus, we doubt that this weak maser is produced by the intrinsic factors of SMM 2. For instance, the potential outflows from massive protostars of SMM 1 may shock the ambient molecular gas of SMM2 and produce a weak water maser at the rear side of SMM2. This scenario is consistent with the lower velocity of the water maser. Therefore, we believe that the existence of this water maser does not necessarily contradict SMM 2’s physical properties derived from the SED and MIR image analyses. Based on the information available, we support

| Object       | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (arcsec) | $\Delta V$ (arcsec) | $\Delta V$ (km s$^{-1}$) | $\theta_{\text{obs}}$ (arcsec) | $R$ (pc) | $M_{\text{vir}}$ ($M_\odot$) |
|--------------|-------------------------------|---------------------|---------------------|-------------------------|-------------------------------|---------|-----------------------------|
| Cloud I      | 21.01 (0.06)                  | 0                   | 1.22 (0.15)         | 126                     | 0.67                          | 170     |
| Cloud II     | 23.84 (0.02)                  | 40                  | 1.60 (0.05)         | 116                     | 0.60                          | 260     |

Note.—The error levels are from the spectral fitting.

*a* The positions of intensity peaks are listed as offsets from the reference coordinates: R.A. (J2000.0) = 19$^h$46$^m$19.9$^s$, decl. (J2000.0) = +24°35′24″.

*b* The virial mass estimated by Zinchenko et al. (1997) is 1080 $L_\odot$, which was derived from the total width of two components in the NH$_3$ ($J, K = (1, 1)$) spectra.

## Table 7

**Parameters of Virial Mass Estimation**

| Object       | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (arcsec) | $\Delta V$ (arcsec) | $\Delta V$ (km s$^{-1}$) | $\theta_{\text{obs}}$ (arcsec) | $R$ (pc) | $M_{\text{vir}}$ ($M_\odot$) |
|--------------|-------------------------------|---------------------|---------------------|-------------------------|-------------------------------|---------|-----------------------------|
| Cloud I      | 21.01 (0.06)                  | 0                   | 1.22 (0.15)         | 126                     | 0.67                          | 170     |
| Cloud II     | 23.84 (0.02)                  | 40                  | 1.60 (0.05)         | 116                     | 0.60                          | 260     |
the hypothesis that SMM 2 is probably a HMSC that may form massive stars or intermediate star clusters eventually.

6. CONCLUSIONS

We have carried out a multiwavelength study of the massive star-forming region S87. The main results are summarized as follows.

1. We identified three submillimeter clumps in S87, labeled SMM 1, SMM 2, and SMM 3. They are estimated to have masses of 210, 140, and 110 $M_\odot$, with average dust temperatures of 41, 21, and 24 K, respectively (from the isothermal gray-body model).

2. We examined molecular line maps from our observations and compared them with the previous results of other authors. We concluded that the star-forming activities in SMM 1 are stimulated by a cloud-cloud collision.

3. We found that HCO$^+$ can trace diffuse gas and NH$_3$ may be destructed by chemical processes in the region harboring MIR sources or exhibiting strong diffuse MIR emission.

4. We calculated the virial masses of the two colliding clouds, which are in good agreement with those estimated from SEDs.

5. The stellar contents and star-forming activities of submillimeter clumps are identified. Their SEDs reveal that these clumps are at various evolutionary stages. SMM 1 and SMM 3 are high-mass and intermediate-mass star-forming regions, respectively. SMM 2 is massive and cold, has no MIR counterpart, and is probably a HMSC. All of these results reveal that the star formation in S87 is at multiple phases.

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