We present the results of $^{12}$CO $J = 2 \rightarrow 1$ observations of the X-ray–bright giant shell complex 30 Doradus in the Large Magellanic Cloud (LMC) using the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). This is the one of the largest H ii complexes in the Local Group. We compare the $^{12}$CO $J = 2 \rightarrow 1$ observations against previously made $^{13}$CO $J = 4 \rightarrow 3$ observations and analyze the spatial distribution of young stellar objects (YSOs) within the cloud using the Spitzer IRAC observations of the 30 Doradus complex. Both peaks of $^{12}$CO $J = 2 \rightarrow 1$ and $J = 4 \rightarrow 3$ emitting clouds coincide with the densest region of the filament in which multiple shells are colliding. The YSOs are clustered in the southern ridge of the warm and dense molecular gas clouds traced by $^{12}$CO $J = 4 \rightarrow 3$, indicating a filamentary structure of star formation throughout 30 Doradus. We also find an excess of Class I YSO candidates close to the clouds, which likely represent the most recent phase of star formation in this region. This is a region where the triggered star formation has actually occurred, and newly formed stars may have produced such a high-velocity outflow through interacting with the surrounding molecular cloud material.

Subject headings: ISM: atoms — ISM: molecules — Magellanic Clouds — submillimeter

1. INTRODUCTION

The Large Magellanic Cloud (LMC) provides an excellent opportunity to study the effects of radiation from young stellar objects (YSOs) on their multiphase interstellar medium (ISM). The LMC has a 27° inclination to the line of sight and has small foreground and internal extinctions, making it possible to map the gas and dust of the ISM in the LMC without confusion with extraneous matter along the line of sight. Unlike stars inside the Milky Way’s Galactic plane, LMC stars are at a common distance from the Earth, but are still close enough that individual stars and their stellar ejecta can be studied in great detail. We specifically chose the 30 Doradus Nebula in the LMC because Kim et al. (2005) detected a high-velocity molecular emission associated with the H ii and H i shells, indicating that this is a very active region of star formation. In addition, the LMC provides an excellent opportunity to study the effects of different UV radiation from stars on their environments in the multiphase ISM, as well as to apply their observed mechanisms to studies on the early evolution of high-redshift, metal-poor galaxies. CO is the chosen species to trace the general distribution of molecular gas because as to apply their observed mechanisms to studies on the early evolution of high-redshift, metal-poor galaxies. CO is the chosen species to trace the general distribution of molecular gas because it is the most abundant observable tracer of H$_2$ and is sensitive to a density regime prevalent in the diffuse molecular gas surrounding dark clouds, molecular cores, and star-forming regions. For Galactic work, the $^{12}$CO line is usually saturated, and an isotope replacement molecule such as $^{13}$CO is needed to obtain better information on column densities and cloud sizes. In the LMC, and therefore also in 30 Doradus, the diffuse CO component is weaker due to lower abundance and higher photodissociation rates. Thus, $^{12}$CO is likely to be tracing virialized clouds and thus to be a reasonable proxy for H$_2$ (Dickman 1978).

We sought to characterize the relationship between the warm and dense core of the molecular clouds traced with $^{12}$CO $J = 4 \rightarrow 3$ and the distribution of young stars across the clouds in the 30 Doradus Nebula. The mid-J CO emissions in the 30 Doradus region have recently been observed with the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), and $^{12}$CO $J = 2 \rightarrow 1$ emission from 30 Doradus reveals the extended structure beyond the $^{12}$CO $J = 4 \rightarrow 3$ emitting region. With the advent of the Spitzer Space Telescope, the distribution of YSOs across the region can be mapped with Spitzer IRAC photometry (Meixner et al. 2006). Jones et al. (2005) provided a comprehensive study of protostars in the giant H ii region complex N159 in the LMC with the Spitzer IRAC observations. A new maser source in 30 Doradus has been found by Oliveira et al. (2006) and massive YSOs have been investigated with L-band imaging (Maercker & Burton 2005). We used color-color and color-magnitude diagrams for Spitzer IRAC sources to study the nature of the distributed populations and their locations in the molecular clouds of 30 Doradus in conjunction with the mid-J CO emissions observed with AST/RO.

2. OBSERVATIONS

The observations of $^{12}$CO $J = 2 \rightarrow 1$ emission lines were performed during the austral winter seasons of 2002 and 2003 at the AST/RO, a 1.7 m diameter, offset Gregorian telescope. AST/RO is located at an altitude of 2847 m at the Amundsen–Scott South Pole Station and is capable of observing at wavelengths between 200 and 1.3 mm (Stark et al. 2001). This site is extremely dry and is therefore a very good position from which to make submillimeter observations (Chamberlin et al. 1997). Since observations of the $^{12}$CO $J = 4 \rightarrow 3$ emission line are described in Kim et al. (2005), we discuss only the observations of $^{12}$CO $J = 2 \rightarrow 1$ emission taken with AST/RO.

Emission from the $^{12}$CO $J = 2 \rightarrow 1$ line was mapped over a 30' x 30' region centered on R.A. = 5h38m40s, decl. = $-$69°06'28"
(J2000.0) with 90" spacing and a beam size of about 180". The position-switching mode was used, and the observation time at each position was typically 7 minutes and 20 s. The receiver used was a 230 GHz superconductor–insulator–superconductor (SIS) waveguide receiver with 79–90 K double-sideband (DSB) noise temperature. Two acousto-optical spectrometers (AOSs; Schieder et al. 1989) were used as back ends. An array AOS having low-resolution spectrometer (LRS) with a bandwidth of 1 GHz (bandpass 1.6–2.6 GHz) and a resolution of 1 MHz corresponding to a velocity resolution of 1.3 km s\(^{-1}\) has been used for 230 GHz observation. LRS has 2048 channels (Kim et al. 2002). AST/RO suffers pointing errors of the order of 1", and the beam sizes (FWHM) were 170"–190" at 230 GHz. Atmosphere-corrected system temperatures ranged from 309 to 364 K at 230 GHz.

The standard chopper wheel calibration technique was employed, implemented at AST/RO by way of regular (every few minutes) observations of the sky and two blackbody loads of known temperature (Stark et al. 2001). Atmospheric transmission was monitored by regular skydips, and known, bright sources were observed every few hours to further check calibration and pointing. At periodic intervals and after tuning, the receivers were manually calibrated against a liquid nitrogen–temperature load and the two blackbody loads at ambient temperature and about 100 K. The latter process also corrects for the dark current of the AOS optical CCDs. The intensity calibration errors became as large as \(\pm 15\%\) during poor weather periods.

Once taken, the data in this survey were reduced using the COMB data reduction package. After elimination of scans deemed faulty for various instrumental or weather-related reasons (\(\sim 10\%\) of the total data set), the data were Fourier-transformed and the second highest amplitude channel was zeroed out, so the well-defined baseline component was removed. Linear baselines were then removed from the spectra. This is shown in Figure 1. The Fourier transforms were performed using fast Fourier transform techniques, and the spectrum is padded with zeros on the right to the next biggest power of 2 (e.g., 2048 channels). After a Fourier transform of the plotted channels in the original full spectrum was completed and selected high-amplitude channels removed, the data were retransformed and inserted back into the original spectrum. The highest amplitude channel was typically the DC offset, which is later removed by baselining, so the second highest amplitude was the one zeroed out. Since the operations were all done in double precision, no loss of accuracy occurred.

To detect YSOs, we used the Spitzer archival data of the 30 Doradus Nebula (AOR key 4379904) observed with an Infrared Array Camera (IRAC). IRAC data consist of four broadband

![Figure 1](image-url)
images, with central wavelengths of 3.6, 4.5, 5.8, and 8.0 μm (Fazio et al. 2004; 0004379904). We first performed an array location–dependent photometric correction on the Basic Calibrated Data (BCD) processed by the IRAC pipeline (ver. S13.2.0). This correction is required because the pipeline flat-fielding based on the zodiacal background is not appropriate for point-source analysis. We next corrected “muxbleed” and “column pulldown” effects, which are image artifacts that appear around bright sources, and matched background levels of overlapping frames. Finally, mosaicked images were made from these corrected images using the MOPEX mosaicker provided by the Spitzer Science Center (SSC).

Source extraction and aperture photometry were performed using the Spitzer Astronomical Point Source Extractor (APEX) with a 5 pixel aperture radius and a 5–10 pixel background annulus. Pixel phase corrections, which amend the dependence of photometry on the location of a source within its peak pixel, were applied to the photometry of channel 1, and aperture corrections were applied to all channels. We then converted flux densities into magnitudes using the IRAC zero-magnitude flux densities. All the values used for corrections and calculations were obtained from the IRAC Data Handbook version 3.0.7

7 See http://ssc.spitzer.caltech.edu/irac/dh.

3. RESULTS

We observed a $^{12}$CO $J = 2 \rightarrow 1$ line emission associated with the 30 Doradus Nebula in the LMC (Fig. 2). The peak of $^{12}$CO $J = 2 \rightarrow 1$ emission is only 40″ away from the peak of $^{12}$CO $J = 4 \rightarrow 3$ emission. Including the pointing error and the beam size of $^{12}$CO $J = 2 \rightarrow 1$ emission, the peak in $^{12}$CO $J = 4 \rightarrow 3$ emission is very close to that in $^{12}$CO $J = 2 \rightarrow 1$ emission. Neither peak is associated with the R136 cluster. Instead, they are surrounded by R135 (WN6h), R139 (O6Iaf/WN)/R140 (WN6), and R144 (WN6h), multiple systems north of the R136 cluster (see Fig. 2).

As expected, the peaks of $^{12}$CO $J = 4 \rightarrow 3$ and $^{12}$CO $J = 2 \rightarrow 1$ emissions are spatially distanced from the peaks of Hα, and the X-ray emissions are shown in Figures 2 and 3. The apparent H II regions and the bright X-ray counterparts in this region indicate that both of the fully ionized regions close to the massive stars, along with their related ionizing radiation escaping from the H II regions, heat the H molecules and keep them dissociated. The morphology of Hα emission is almost identical to that of 8 μm emission (Fig. 4), a tracer of polycyclic aromatic hydrocarbon (PAH) emission, indicating that the PAH is only partially destroyed in the H II region. The poor correlation between 8 μm and CO emission is in contrast to the relatively good correlation...
found on larger scales by SAGE (Meixner et al. 2006) and SINGS (Regan et al. 2006).

High-velocity $^{12}\text{CO} J = 4 \rightarrow 3$ emitting gas detected in this region (Kim et al. 2005; Kim 2006) and the morphology of $^{12}\text{CO} J = 4 \rightarrow 3$ emission indicate that the bulk of the CO emission must result from the entrainment of ambient atomic and molecular cloud gas by the stellar winds colliding with one another seen in the H$\alpha$ image (Fig. 2). Using the best estimate of the luminosity mass for $^{12}\text{CO} J = 4 \rightarrow 3$ outflow (Kim et al. 2005), $(2.6 \pm 1.6) \times 10^4 M_\odot$, and the dynamical age of the shells, 10 Myr, we estimate the rate of ambient gas entrainment to be $M_{\text{flow}} = 2.6 \times 10^{-3} M_\odot$ yr$^{-1}$ with the velocity, approximately $v \sim 18$ km s$^{-1}$ (Kim 2005). The momentum injection rate is $P_{\text{flow}} = 1.3 \times 10^{-11} M_\odot$ km s$^{-1}$ yr$^{-1}$, and the mechanical luminosity is estimated to be $L_{\text{flow}} = 5.4 \times 10^5 L_\odot$.

We detected the near-IR sources associated with the molecular cloud core in the $^{12}\text{CO} J = 2 \rightarrow 1$ and $^{12}\text{CO} J = 4 \rightarrow 3$ emitting clouds in the 30 Doradus Nebula by utilizing Spitzer GTO IRAC observations. We identified YSO candidates among these sources from the color-color diagram of $[3.6 \mu\text{m} - 4.5 \mu\text{m}]$ versus $[5.8 \mu\text{m} - 8.0 \mu\text{m}]$ (Fig. 5a) and classified them into three groups based on the criterion suggested by Allen et al. (2004). Since the Fitzpatrick and Savage nebular extinction curve component for 30 Doradus is $0.17 \pm 0.17$ (Hill et al. 1993), it can only change the colors of $[3.6 \mu\text{m}] - [4.5 \mu\text{m}] = 0.007$ mag and $[5.8 \mu\text{m}] - [8.0 \mu\text{m}] = 0.01$ mag (Rieke & Lebofsky 1985). This is too small to affect the classification. These classes show the evolutionary sequence from Class I to Class III. Class I objects are surrounded by infalling envelopes, Class II objects have accretion disks, and Class I/II objects are in an intermediate state between Classes I and II (Kenyon & Hartmann 1995; Megeath et al. 2004). They are denoted by open circles (Class I), squares (Class II), and diamonds (Class I/Class II) in Figure 5. Class III objects were excluded from the classification because they have the SEDs of stellar photospheres and cannot be distinguished from foreground or background stars. Figure 5b shows the location of these objects on the color-magnitude diagram of $[3.6 \mu\text{m} - 8.0 \mu\text{m}]$ versus $8.0 \mu\text{m}$ using the above symbols. Since the brightness of $8 \mu\text{m}$ emission can be affected by PAH emission arising from the 30 Doradus Nebula, we present the color-color diagram of $[3.6 \mu\text{m} - 4.5 \mu\text{m}]$ versus $[4.5 \mu\text{m} - 5.8 \mu\text{m}]$ in Figure 6, which also shows the locations of the late spectral types from Jones et al. (2005) along the vertical axis. We have used these for distinguishing the YSOs from the giants and supergiants. It confirms that the classified objects in Figure 5a fall in a relatively well-defined region of the color–color diagram in Figure 6. The distinction is clear.

The only problem is that the 30 Dor-09 object identified as Class II in Figure 5a shows much redder $[4.5 \mu\text{m} - 5.8 \mu\text{m}]$ color, $\sim 1.7$. This object was identified as an M red supergiant star, Dor IR 10, by McGregor & Hyland (1981) using the JHK photometry and IR spectroscopy. They also found 11 other M red supergiants in 30 Doradus, but we could not locate any corresponding sources associated with our classified YSO’ catalog. A previous study

![Figure 3](image1.png)

![Figure 4](image2.png)
Fig. 5.—(a) Color-color diagram of [3.6 μm − 4.5 μm] vs. [5.8 μm − 8.0 μm]. Detected infrared sources are classified based on the criterion suggested by Allen et al. (2004) and Megeath et al. (2004). Open circles represent Class I objects, and diamonds represent Class I/II objects. Squares represent Class II objects, and filled circles represent both Class III objects and ordinary stars. The box represents the region of Class II sources (Allen et al. 2004). The solid line shows the division between the Class I and Class I/II candidates. (b) Color-magnitude diagram of [3.6 μm − 8.0 μm] vs. 8.0 μm using the same symbols.

(Brandner et al. 2001) reported 20 Class I protostars and Herbig Ae/Be candidates near the R136 cluster in the 30 Doradus complex using the JHK color-color diagram. Eight of these sources (Table 1) could be matched with the YSO population traced by the present IRAC data analysis. Class I objects show strong [3.6 μm − 8.0 μm] color excess, with color indices of approximately 4, while most of Class II objects show a relatively weak [3.6 μm − 8.0 μm] color excess, with indices from 1 to 2.

4. DISCUSSION

The H i aperture synthesis mosaicked map of the LMC with a spatial resolution of 50″, created by combining 1344 separate pointings of the Australia Telescope Compact Array (ATCA), shows an overall clumpy H i distribution featuring holes, shells, loops, filaments, and bubbles (Kim et al. 1998, 1999, 2003). The H i supergiant shells occupy a large volume of the ISM, and a large number of giant shells, contained within each supergiant, are colliding with one another. The many shells observed often overlap and are interacting with one another, such as in the vicinity of the 30 Doradus complex, where very active star formation has been happening simultaneously in many different centers.

Several of the smaller shells form on the rims of supergiant shells and are found in regions of very active star formation in the LMC (Kim et al. 1999). Using recent submillimeter observations of the LMC supershells and superbubbles in the LMC, AST/RO aimed to look for the place where the triggered star formation had happened (Kim et al. 2004) and found the 12CO J = 4 → 3 emission toward the rim of the expanding giant H ii complex in 30 Doradus. They detected a possible high-velocity molecular emission associated with the H ii and H i shells in the 30 Doradus Nebula. This observational fact has been interpreted as the result of self-propagating star formation, where gravitational instabilities in the swept-up material of the supergiant shell caused fragmentation and a new round of star formation. Newly formed stars may have produced such high-velocity molecular outflows by interacting with the surrounding molecular cloud material. Outflows and jets are commonly seen in the ambient medium of young stellar objects.

It is commonly accepted that stars form in molecular clouds by the gravitational collapse of dense gas. Both low- and high-mass young stellar objects are embedded in the parent molecular cloud and heat the surrounding gas. Outflows from YSOs often accelerate gas and are observed as molecular outflows. The radiative heating and magnetic fields are likely to be the main energy sources driving outflows for both low- and high-mass YSOs. Using the recent Spitzer IRAC observations of the 30 Doradus complex, we examined young stellar objects traced by IRAC data that might be associated with the high-velocity components of 12CO J = 4 → 3 emitting clouds.

A total of 41 YSO candidates falling close to the core of the 12CO J = 2 → 1 and 12CO J = 4 → 3 emitting clouds were detected and classified from the IRAC survey of 30 Doradus. We present our photometry results and classes in Table 1. Figure 4 presents the spatial distribution of the detected YSO candidates toward the relatively dense molecular cloud core found in the

Fig. 6.—Color-color diagram of [3.6 μm − 4.5 μm] vs. [4.5 μm − 5.8 μm]. The 41 YSO candidates are marked with the same symbols used in Fig. 5. We plot the locations of the late spectral types from Jones et al. (2005) along the vertical axis.
$^{12}\text{CO} \ J = 4 \to 3$ and $^{12}\text{CO} \ J = 2 \to 1$ emitting gas. No strong association is found between the location of YSO candidates and the dense molecular cloud core, as seen in Figure 4. However, Class I candidates that are thought to be protostars surrounded by dusty infalling envelopes and that exhibit significant near-infrared extinction from their envelopes are very close to the peaks of $^{12}\text{CO} \ J = 4 \to 3$ and $^{12}\text{CO} \ J = 2 \to 1$ emissions. Conspicuously, the Class I YSO 30 Dor-30 is detected near the high-velocity component of $^{12}\text{CO} \ J = 4 \to 3$ emission. Thirteen YSO candidates are concentrated in the southern region of the $^{12}\text{CO} \ J = 2 \to 1$ emitting cloud, about 30 pc away from the molecular cloud core. Association densities are likely to be as low as $10^{-4}$ stars pc$^{-2}$ at the distance of the LMC (Feast 1991). It is notable that the relationship between the number of YSO candidates and their radial distribution from the core (Fig. 4) reveals that more recently formed stars (Class I objects) are distributed closer to the molecular cloud core.

Table 1 presents a list of YSO candidates near the 230 GHz $^{12}\text{CO} \ J = 2 \to 1$ emission core in the 30 Doradus Complex. The table includes the ID, R.A. (J2000.0), Decl. (J2000.0), and distances in 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm, as well as a Class designation.

Figure 7 presents an analysis measuring the distance of the YSOs to the core of the CO cloud. The method performed was similar to one presented by Teixeira et al. (2006), except that the measured variable was different. We utilized a Monte Carlo simulation to analyze the difference between the observed spatial distribution and a randomly generated star field. We created 10,000 star fields with an equal number of randomly and uniformly placed YSOs in an equal observing area. The average distance to the cloud core of these objects was calculated and presented in a histogram to be compared with the distances of the observed YSOs. These comparisons show a structural arrangement of YSOs with respect to the core of the CO cloud in the 30 Doradus Nebula, likely to be a filamentary distribution. In the total distribution of all classes, we find that there is a probability of 0.15% of having more than nine objects placed between 200$''$ and 300$''$ from the core. This seems to be mostly due to the Class I YSOs, given that a 0.02% probability exists of finding more than six Class I YSOs at

\[ \text{Distance} = \text{R.A.} - \text{Decl.} \]

\[ \text{Class} = \begin{cases} \text{I} & \text{if} \ 3.6 \mu m \leq 12.17 \pm 0.03 \\ \text{II} & \text{if} \ 3.6 \mu m > 12.17 \pm 0.03 \end{cases} \]

\[ \text{Class} = \begin{cases} \text{I} \ a & \text{if} \ 4.5 \mu m \leq 8.9 \pm 0.02 \\ \text{II} & \text{if} \ 4.5 \mu m > 8.9 \pm 0.02 \end{cases} \]

\[ \text{Class} = \begin{cases} \text{I} \ a & \text{if} \ 5.8 \mu m \leq 9.8 \pm 0.02 \\ \text{II} & \text{if} \ 5.8 \mu m > 9.8 \pm 0.02 \end{cases} \]

\[ \text{Class} = \begin{cases} \text{I} & \text{if} \ 8.0 \mu m \leq 9.2 \pm 0.02 \\ \text{II} & \text{if} \ 8.0 \mu m > 9.2 \pm 0.02 \end{cases} \]

\[ \text{Class} = \begin{cases} \text{I} \ a & \text{if} \ \text{Class} \text{I/II} \ 0.02 \leq 10.0 \pm 0.02 \\ \text{II} & \text{if} \ \text{Class} \text{I/II} > 10.0 \pm 0.02 \end{cases} \]
that same distance. We can see that Class I/II YSOs are absent at this distance, but using the next bin (300–400”), we find that at its peak, the Class I/II YSOs have a probability of 3.41% of having more than four objects. Class II objects also follow the general distribution of the other two previous classes, but are too few; therefore, tests were inconclusive.

5. CONCLUSION

AST/RO observations have revealed that the peaks of $^{12}$CO $J = 2 \rightarrow 1$ and $^{12}$CO $J = 4 \rightarrow 3$ emission are located at the rims of colliding H II shells (Chu & Kennicutt 1994) in the very active star-forming region of the 30 Doradus complex in the LMC. Previous studies by Kim et al. (2005) showed that $^{12}$CO $J = 4 \rightarrow 3$ emission has a high-velocity component corresponding to the peak of the emission. This region must be the place where triggered star formation had happened, since newly formed stars may have produced such a high-velocity molecular outflow by interacting with the surrounding molecular cloud material. Using the recent Spitzer IRAC observations of the 30 Doradus complex, we found that Class I YSOs candidates tend to be associated with the high-velocity component of $^{12}$CO $J = 4 \rightarrow 3$ emitting clouds. We also discovered that the YSOs are clustered in the southern ridge of the relatively warm and dense molecular cloud cores traced by $^{12}$CO $J = 4 \rightarrow 3$, indicating a filamentary structure of star formation.

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