CLUSTERED AND TRIGGERED STAR FORMATION IN W5: OBSERVATIONS WITH SPITZER

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ABSTRACT

We present images and initial results from our extensive Spitzer Space Telescope imaging survey of the W5 H II region with the Infrared Array Camera (IRAC) and Multiband Imaging Photometer for Spitzer (MIPS). We detect dense clusters of stars, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520. At 24 μm, substantial extended emission is visible, presumably from heated dust grains that survive in the strongly ionizing environment of the H II region. With photometry of more than 18,000 point sources, we analyze the clustering properties of objects classified as young stars by their IR spectral energy distributions (a total of 2064 sources) across the region using a minimal-spanning-tree algorithm. We find ~40%–70% of infrared excess sources belong to clusters with ≥10 members. We find that within the evacuated cavities of the H II regions that make up W5, the ratio of Class II to Class I sources is ~7 times higher than for objects coincident with molecular gas as traced by 12CO emission and near-IR extinction maps. We attribute this contrast to an age difference between the two locations and postulate that at least two distinct generations of star formation are visible across W5. Our preliminary analysis shows that triggering is a plausible mechanism to explain the multiple generations of star formation in W5 and merits further investigation.

Subject headings: H II regions — infrared: stars — ISM: globules — stars: early-type — stars: formation — stars: pre–main-sequence

Online material: machine-readable tables

1. INTRODUCTION

Star formation is a self-regulating process—once massive stars form they immediately begin to disrupt their natal environment with their stellar winds and the emission of ionizing radiation. Eventually their parental molecular clouds are destroyed, halting further star formation. However, it has also been argued that the energy input by these massive stars can promote and induce subsequent star formation in the surrounding molecular gas before it disperses, above which would be produced without external forcing. This process is given the name “triggering” (see Elmegreen 1998 and Zinnecker & Yorke 2007 for reviews of this subject). It is vital to understand the balance of cloud destruction and triggered star formation if we are to develop a theory that explains the morphology and evolution of star-forming regions, star formation efficiencies, and the initial mass function (IMF) of stars in clusters. It also has relevance for star formation on galactic scales in understanding how star formation progresses with time, and indeed how the spiral structure of galaxies evolves with time (Seiden & Schultman 1990; Jungwiert & Palous 1994). Feedback in star formation can be clearly observed in bright-rimmed clouds, where an edge-on molecular cloud is externally illuminated by nearby young massive stars, creating a cross-section of the photoevaporation process as the ionization fronts they produce advance into the molecular cloud.

Two triggering mechanisms are of interest in regard to W5. The first is the creation of an ionized H II region bubble by an initial generation of massive stars within their parental molecular cloud and its subsequent expansion. In this “collect-and-collapse” mechanism, investigated analytically by Whitworth et al. (1994) and numerically by Dale et al. (2007), the expansion creates a shock front that sweeps up neutral material ahead of it as it progresses outward. The gas accumulated eventually exceeds a critical threshold for collapse and gives rise to a second generation of star formation. Second, inhomogeneity in the ISM often leads to small clumps of material remaining exposed inside an H II region. Given this environment, the high pressure of the surrounding ionized gas has been suggested as a mechanism to compress the clumps and form stars (Stutzki et al. 1988).

The star-forming region W5 is a part of the chain of molecular clouds W3/4/5 (Westerhout 1958). Its distance has not been definitively established—Becker & Fenkart (1971) found a photometric distance of 2.2 kpc, but more recently Hillwig et al. (2006) found that a distance of 1.9 kpc gave the most consistent results of evolutionary model fits to stellar radii in W5. Xu et al. (2006) found a distance to the neighboring region W3OH of 1.95 ± 0.04 kpc using maser parallaxes. We adopt a distance to W5 of 2 kpc as a conservative intermediate between these estimates. W5 is a relatively isolated star-forming region, with an apparently simple morphology. Optical imaging shows it is made up of two roughly circular adjoining H II regions W5 East and W5 West (Karr & Martin 2003), containing one and four O stars, respectively. At least two of the four O stars in W5 West are multiple systems (Hillwig et al. 2006). Both 12CO and 21 cm radio emission (see Normandeau et al. 1996) demonstrate the same overall shape—12CO emission traces the molecular hydrogen gas in W5, which appears as two broken rings of emission. Figure 1 shows a map of 12CO (λ = 2.6 mm) emission integrated over the range −28 to −47 km s−1, made using observations with the 14 m FCRAO telescope. The bulk of the emission is found between a velocity of −31 and −47 km s−1 and thus is likely roughly in the same plane. In this image, following the naming...

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scheme of Wilking et al. (1984), to the northwest of HD 17505 is the molecular cloud W5NW, in between HD 18326 and BD +60 586 is W5NE, and to the east of HD 18326 is W5A. Due to this relatively simple morphology, W5 presents a useful test case for investigating models of triggered star formation and the influence of massive star formation on its surroundings.

In this paper we present initial results from our mid-IR Spitzer survey of W5 with the IRAC and MIPS instruments. In § 2 we describe our observations and data reduction techniques, and we discuss our classification and clustering analysis in § 3. In § 4 we perform a simplified trial investigation of triggered star formation models as a means of explaining the observed distribution of young stars in different evolutionary states across the region. In § 5 we present our conclusions and directions of future work.

2. OBSERVATIONS AND DATA REDUCTION

W5 was observed with the Spitzer IRAC instrument (Fazio et al. 2004) in all four bands (3.6, 4.5, 5.8, and 8.0 μm). The observations were broken down into three rectangular Astronomical Observing Requests (AORs) covering ~1.8' × 1.6', in order to observe at multiple rotation angles and help minimize artifacts aligned along columns or rows of the array. In Table 1 we list the dates and coordinates of each AOR. Each AOR had a coverage of one high dynamic range (HDR) frame. HDR mode results in a 10.4 and 0.4 s exposure being taken at each position in each map. We used software tools (clustergrinder) developed by one of us (R. A. G.) to produce final image mosaics from these data in each wavelength band. The clustergrinder tool incorporates all necessary image treatment steps, for example, saturated-pixel processing and distortion corrections (see Gutermuth et al. 2008a for a more complete description of the processing performed). Clustergrinder uses the short 0.4 s exposures only in saturated or near-saturated regions, so that the combined map has an effective total integration time of 3 × 10.4 = 31.2 s in most of the overlapping areas. We also incorporated in our data processing archival data covering AFGL 4029 (from Spitzer GTO program PID 201; Allen et al. 2005), at the eastern end of W5.

The MIPS (Rieke et al. 2004) observations were carried out on 2006 February 23 UT under our GO-2 program, PID 20300. Images were taken in scan map mode using the medium scan speed, for an average exposure time of 41.9 s pixel−1 once frames were combined. The raw data were processed with pipeline version S13.2.0. We produced final mosaics using the MIPS

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Table 1: Astronomical Observing Requests

| AORKEY        | Date (UT) | Coordinates (J2000.0) | IRAC Reduction Pipeline Version |
|---------------|-----------|-----------------------|---------------------------------|
| 14507776      | 2006 Sep 20 | R.A. 02 53 32.9 Decl. +60 25 59.1 | S14.0.0                         |
| 14507008      | 2006 Sep 28 | R.A. 02 53 43.5 Decl. +60 21 57.2 | S14.0.0                         |
| 14508544      | 2007 Feb 16 | R.A. 02 53 54.2 Decl. +60 17 55.2 | S15.3.0                         |

**Note.** Units of right ascension are hours, minutes, and second, and units of declination are degrees, arcminutes, and arcseconds.
instrument team Data Analysis Tool, which calibrates the data and applies a distortion correction to each individual exposure before combining (Gordon et al. 2005). We used only the 24 μm band data for our analysis in this paper, since strong background emission dominates at the longer wavelength (70 and 160 μm) bands of MIPS and lower sensitivity reduces the number of detectable objects to a level that is not useful for the present study.

In Figure 2 we present a three-color IRAC image of W5, using the color scheme: blue=3.6 μm, green=4.5 μm, and red=8.0 μm. In Figure 3 we show our MIPS 24 μm mosaic. Figure 4 presents a composite image incorporating MIPS, with blue=4.5 μm, green=5.8 μm, and red=24 μm (MIPS).

We carried out point-source extraction and aperture photometry of all point sources on the final IRAC mosaics with PhotVis version 1.10beta3. PhotVis is an IDL GUI-based photometry visualization tool (see Gutermuth et al. 2004) that utilizes DAOPHOT modules ported to IDL in the IDL Astronomy User’s Library (Landsman 1993). We used PhotVis to visually inspect the detected sources in IRAC bands 1, 3, and 4, adding sources not detected automatically but clearly visible in the images with the GUI tool, and rejected any structured nebulosity or cosmic rays mistaken for stellar sources by the automatic detection algorithm. To save time, we did not visually check the band 2 photometry in this manner. Instead, we took the cleaned band 1 source list as the start point for finding objects in the image and extracted photometry at each position. Radii of the apertures and inner and outer limits of the sky annuli were 2.4″, 2.4″ and 7.2″, respectively. The resulting photometry was calibrated using large-aperture in-flight measurements of standard stars, with an appropriate aperture correction in each channel to correct for the smaller apertures used in this study. In this paper we restrict our source catalog to only those objects with magnitude error ≤0.2 in all four IRAC filters, a total of 18,518 objects.

We estimate the completeness in each IRAC filter by breaking up each image into a 100 × 100 pixel grid, adding artificial stars to each grid cell and counting the number retrieved as a function of magnitude. Averaged over the whole W5 field, our source catalog is 90% complete to a magnitude of 15.5 at 3.6 μm, 15.5 at 4.5 μm, 14.0 at 5.8 μm, and 12.7 at 8 μm. The completeness is less in regions of bright diffuse emission: ~14 at 3.6 and 4.5 μm, ~11 at 5.8 μm, and ~9.5 at 8.0 μm.

We conducted point-source extraction and aperture photometry of point sources in the 24 μm MIPS mosaic using the point-spread function–fitting capability in IRAF DAOPHOT (Stetson 1987). We visually inspected the image to pick out point sources not automatically detected due to bright diffuse emission evident throughout the image. We match the four-band IRAC source list to the MIPS catalog using a 2″ search radius, selecting the object closest to the MIPS point-spread function centroid in cases where more than one IRAC object is a match. Of the 1874 MIPS objects that match with entries in our IRAC four-band list, 6 had a second object within the 2″ search radius which possibly contributes to its 24 μm flux. We consider this a small effect on our analysis.

3. ANALYSIS

3.1. Source Classification

In order to characterize the progress of star formation throughout W5 it is important to establish the evolutionary status of stars within the region. The presence of massive O stars (Hillwig et al. 2006) and significant molecular material in W5 (Lada et al. 2006) are key indicators of ongoing star formation. By analyzing the photometric data obtained from the Spitzer IRAC and MIPS observations, we aim to identify and classify sources based on their photometric properties.

We begin by examining the color-magnitude diagrams (CMDs) constructed from the photometric data in the IRAC and MIPS bands. The CMDs provide a visual representation of the evolutionary status of the sources, with different evolutionary stages typically occupying distinct regions in the CMD.

In the IRAC bands, the sources can be classified as follows:

- Young stars: sources located in the blue region of the CMD, characterized by high temperatures and low masses. These sources are typically OB stars and early-type giants.
- Intermediate-age stars: sources located in the red region of the CMD, characterized by intermediate temperatures and masses. These sources are typically B and A-type stars.
- Old stars: sources located in the upper right region of the CMD, characterized by low temperatures and high masses. These sources are typically red giants and supergiants.

In the MIPS bands, the sources can be classified as follows:

- Warm dust: sources located in the infrared region of the CMD, characterized by low temperatures and high masses. These sources are typically young stellar objects (YSOs) and pre-main-sequence stars.
- Intermediate-age dust: sources located in the intermediate region of the CMD, characterized by intermediate temperatures and masses. These sources are typically evolved stars.
- Old dust: sources located in the upper right region of the CMD, characterized by low temperatures and high masses. These sources are typically old stars.

By comparing the photometric data from the IRAC and MIPS bands, we can refine our classification and gain insights into the evolutionary status of the sources.

The analysis of the photometric data reveals that W5 contains a diverse population of stars, ranging from young OB stars to evolved giants. The sources exhibit a wide range of properties, from hot, massive stars to cool, low-mass dwarfs. The presence of YSOs and pre-main-sequence stars in W5 indicates ongoing star formation, while the presence of evolved stars suggests that the region has a rich history of star formation.

The results of this analysis will be presented in the next section, along with a discussion of the implications for the evolutionary status of stars in W5.

**Fig. 2.** — W5 Spitzer IRAC bands one-, two-, and four-color composite. Bright emission from PAH grains at 8 μm traces the boundary of the H ii region giving the bright pinkish color. Dense clusters of stars surround the O stars in the interior, with smaller clusters appearing amid the diffuse PAH emission.
1978), suggest that the stars associated with the region will be of relatively young age ($< 10^7$ yr). Recently formed stars exhibit infrared excess emission in their spectra above that produced by the stellar photosphere. This excess emission arises from heated dust, either within the circumstellar material close to the young star, perhaps falling onto it as a part of protostellar collapse, or left behind after the end of star formation. This material gradually disappears with time, and hence the excess emission evolves as a function of stellar age. We make use of this by measuring $\alpha_{\text{IR}}$ (see, e.g., Lada 1987; Stahler & Palla 2005):

$$\alpha_{\text{IR}} = \frac{d \log(\lambda F_{\lambda})}{d \log \lambda},$$

the value of which decreases with the progression of the star’s evolutionary state, whether through its own aging or the effects of its environment.

In the case of most surveys of star-forming regions, including W5, infrared colors serve as proxies for directly measuring $\alpha_{\text{IR}}$. Schemes developed by Whitney et al. (2003), Allen et al. (2004), Megeath et al. (2004), and Muzerolle et al. (2004) and tested by (for example) Hartmann et al. (2005) have demonstrated the power of this technique for classifying young stellar objects using Spitzer IRAC and MIPS photometry. The classification scheme we use is described fully in Gutermuth et al. (2005), which itself is based on the NICE and NICER algorithms of Lada et al. (1994) and Lombardi & Alves (2001). The map has an angular resolution of $\sim 3.5''$ and is sensitive up to $A_V \sim 15$. However, the map is limited by the sensitivity of the 2MASS survey. As a result, $A_V$ values in the map above $\sim 3$ may be underestimates of the true extinguishing column through the entire cloud, since objects behind are too faint to be detected. This is only the case for $< 1\%$ of pixels in the map, so we ignore this effect for our analysis. With $A_V$ values in hand for all sources, we deredden their IRAC magnitudes using the IR extinction law presented in Flaherty et al. (2007), assuming each source is seen behind the full extinguishing column in each case.

We first remove star-forming (PAH) galaxies and weak-line AGNs via a series of cuts in the four-band IRAC color-color diagrams after the procedure developed by Gutermuth et al. (2008a). Because W5 is $\sim 4$ times more distant than the nearby regions studied by Gutermuth et al., this filter removes many apparent young stellar objects (YSOs). In the Appendix we discuss how we characterize and account for this effect in our subsequent analysis. Next we filter out unresolved shocked blobs of PAH emission by cutting objects with a large 4.5 $\mu$m excess, i.e., very red $[3.6] - [4.5]$ color (Smith et al. 2006). We categorize the remaining—presumably stellar—sample primarily relying largely on the $[4.5] - [5.8]$ color to discriminate among SED classes. In Figure 5 we show IRAC color-color diagrams for sources in W5, marking the location of protostars (Class I/0, red dots), stars with disks (Class II, green dots), and stars exhibiting...
Fig. 4.—Composite of emission in IRAC bands 2 and 4, plus MIPS 24 μm. Emission at 24 μm—presumably from heated dust—fills the interior of the H II region cavities, see § 3.2.

Fig. 5.—Left: [3.6] – [4.5] vs. [4.5] – [5.8]; right: [4.5] – [5.8] vs. [5.8] – [8.0] IRAC color-color diagrams used for identifying candidate protostars. Black dots: Class III; green: Class II; red: Class I; yellow: transition disk candidates. AGN and PAH galaxy candidates are not included here.
only photospheric colors (Class III, black dots) as identified using our scheme.

We also use 2MASS $H$ and $K_S$ photometry, combined with IRAC 3.6 and 4.5 $\mu$m data to classify objects lacking either an IRAC [5.8] or [8.0] detection. To make sure the 2MASS sources have reliable photometry we require a magnitude error $\lesssim$0.1 in both $H$ and $K_S$ bands. We first deredden the photometry in these four bands and then identify IR excess sources as those having red [3.6] – [4.5] and $K_S$ – [3.6] colors. The results are shown in Figure 6 (left).

MIPS 24 $\mu$m photometry provides us with additional classification information. Figure 6 (right) shows the color-color diagram combining MIPS and IRAC photometry. Stellar sources not classified as either Class I or Class II by their IRAC or near-IR colors may still have red colors ([5.8] – [24] > 1.5) and thus be candidate “cold disk” or “transition disk” objects—in other words, Class II objects with significant clearing of their inner disk region (see, for example, Muzerolle et al. 2004; Lada et al. 2006; Cieza et al. 2007; Najita et al. 2007; Flaherty & Muzerolle 2008; Brown et al. 2008). These are marked with yellow dots in Figures 5 and 6. MIPS photometry is also used as a check on the AGN/galaxy/shocked-blob filtering and Class I classification. AGN candidates with bright MIPS detection can be reclassified as protostars, and Class I objects with insufficiently red [5.8] – [24] or [4.5] – [24] colors are demoted to Class II.

Finally, we also visually inspected the SEDs of all objects in Class I and Class II (a total of 2064 objects), where available making use of 2MASS $JHK_S$ and/or 24 $\mu$m photometry. In most cases only IRAC four-band data were present. We give the full list of objects, Class I, Class II, Class III, and transition disk candidates, in Table 2. We list source coordinates and photometry in near-IR $JHK_S$ (from 2MASS) and Spitzer bands and give a column denoting infrared SED source class and a flag column for objects with unusual SEDs. Objects are sorted and indexed by ascending right-ascension order. We note Class I sources with bright emission at 24 $\mu$m and very red IRAC $–$ 24 $\mu$m color $([X] - [24]) > 4.5$, where $X$ is the magnitude in any of the four IRAC bands as the subclass “deeply embedded protostars” in the table. Table 3 gives a summary of the classification results.

In Figure 7 we show the spatial distribution of young stars (Class I and deeply embedded protostars, and Class II and transition disk candidates) in W5 overlaid on the IRAC 4.5 $\mu$m image. Class I and Class II sources are marked in red and green, respectively, and transition disk candidates and embedded protostars with yellow and blue dots, respectively. O stars are labeled and marked with white asterisks.

### Table 2: W5 Source List

| ID | R.A. (deg) | Decl. (deg) | $J$ (mag) | $H$ (mag) | $K_S$ (mag) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) | [24] (mag) | Type | Flag |
|----|-----------|------------|---------|---------|-----------|----------|----------|----------|----------|----------|------|------|
| 1  | 41.081526 | 60.510607 | 15.34(06) | 13.69(03) | 13.04(03) | 12.60(01) | 12.50(01) | 12.36(04) | 12.47(07) | ... | III  |
| 2  | 41.098560 | 60.682772 | 12.78(03) | 12.39(02) | 11.74(02) | 11.36(01) | 11.35(01) | 11.20(01) | 11.12(03) | ... | III  |
| 3  | 41.10737 | 60.67424 | 13.30(02) | 12.26(02) | 11.88(02) | 11.63(01) | 11.72(01) | 11.43(04) | 11.5(01) | ... | III  |
| 4  | 41.109056 | 60.60875 | 12.01(02) | 12.52(04) | 12.29(03) | 12.18(01) | 12.12(01) | 11.81(05) | 10.67(05) | ... | II    |
| 5  | 41.109473 | 60.515686 | 12.52(02) | 12.09(02) | 11.96(02) | 11.94(01) | 11.94(01) | 11.88(02) | 12.02(05) | ... | III  |
| 6  | 41.112052 | 60.519115 | 13.27(02) | 12.53(02) | 12.12(02) | 11.95(01) | 11.86(01) | 11.75(02) | 11.74(05) | ... | III  |
| 7  | 41.116165 | 60.509403 | 14.20(03) | 13.73(03) | 13.53(04) | 13.48(01) | 13.52(01) | 13.54(08) | 13.43(17) | ... | III  |
| 8  | 41.128907 | 60.512183 | 14.90(04) | 14.12(04) | 13.67(05) | 13.41(01) | 13.32(01) | 13.36(08) | 13.78(19) | ... | III  |
| 9  | 41.138946 | 60.536046 | 13.96(03) | 12.39(02) | 11.74(02) | 11.36(01) | 11.35(01) | 11.20(01) | 11.12(03) | ... | III  |
| 10 | 41.130516 | 60.673029 | 12.78(03) | 12.30(03) | 12.03(03) | 11.89(01) | 11.82(01) | 11.74(02) | 11.7(05) | ... | III  |

Notes.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Values in parentheses by photometry signify error in last two digits of magnitude value. Right ascension and declination coordinates are J2000.0.

* Source class as defined in text.

* Sources with unusual SED shape are flagged with a “v” or uncertain source class with a question mark.
3.2. Spatial Distribution of Young Stars in W5

Figure 7 clearly shows that neither Class I nor Class II type objects in W5 are distributed uniformly, but rather (for the most part) in clustered, or filamentary formations. Within the larger cavity of W5W, clusters of Class II YSOs can be seen centered on the O stars HD 17505, HD 17520, and BD +60 586 of the open cluster OCl 364 (Alter et al. 1970). Similarly, in the smaller W5E bubble a cluster of young stars is visible centered on the O star HD 18326. Small clusters of Class I and Class II objects are also visible in the large region of bright diffuse emission to the northwest of HD 17505. Based on the higher proportion of Class I relative to Class II stars (quantified in §3.4), these are probably younger clusters just emerging from their parental molecular cloud.

Extending out from the central clusters of Class II objects are more filamentary groupings of stars. In W5 West, a chain of young stars appears to extend from the cometary bright rimmed clouds at the southern rim of the bubble (object 11 in the survey of Sugitani et al. 1991) up to the clusters around HD 17505 and HD 17520, and through the cluster around BD +60 586 to the bright rimmed clouds on the eastern rim of the bubble. In W5 East a chain of young stars extends east-west from each of the two peaks of AFGL 4029 (Price & Murdock 1983) through the cluster around HD 18326 to the bright PAH ridge that marks the western edge of the bubble.

Numerous protostars (Class I objects) are seen in projection on the cloud rim at the PAH emission/Hβ region cavity boundaries. For example, the bright-rimmed clouds that make up the eastern border of W5 East, the bright rimmed clouds at the north-eastern rim of W5 West, and the cometary clouds at the southern rim of W5 West all contain several Class I objects. Several isolated cloud remnants and small “elephant trunk” formations within the Hβ region cavity also contain Class I or Class II objects—these are listed in Table 4. We give a type to each object to distinguish the different morphologies. These objects are interesting candidates for triggered star formation on small scales; see the discussion in §4.3. Figure 8 shows several examples of these objects.

The influence of star formation on its environment is clear to see in both the IRAC (Fig. 2) and MIPS images (Figs. 3 and 4). Bright diffuse emission in the four IRAC filters (Draine & Li 2007) is only present around the edge of the two main Hβ region bubbles in roughly ringlike structures, and brightly lit up over the molecular clouds W5NE and W5NW. Presumably, the PAHs responsible for much of the emission in IRAC bands 1, 3, and 4 are destroyed in the harsh ionizing environment of the Hβ region. At 24 μm the morphology is similar in the bubbles’ rims, but very different diffuse emission is seen in the interior

![Source distribution overlaid on the MIPS 24 μm gray-scale image. Red: Class I; green: Class II; yellow: transition disk candidates. O stars are marked with asterisks.](image-url)
surrounding the 5 O stars (as labeled in Fig. 3). Seen in numerous massive star-forming regions by Churchwell et al. (2006), Smith & Brooks (2007), and recently Harvey et al. (2008), this additional component of diffuse emission is consistent with the picture of Créte et al. (1999) whereby emission within H II regions at mid-IR wavelengths is produced by heated larger dust grains (radius $> 12 \mu m$) that survive being destroyed by ionizing radiation. As Draine & Li (2007) have shown, emission in IRAC bands 1 and 4 is much more sensitive to the PAH mass fraction than is emission in the MIPS 24 $\mu m$ band. Further, 24 $\mu m$ band emission increases rapidly when the interstellar radiation field (ISRF) rises to $10^4$–$10^5$ times the local value. Thus, a region with low PAH mass fraction but high ISRF can have enhanced 24 $\mu m$ emission, but will have low IRAC 3.6 and 8.0 $\mu m$ PAH emission. The morphology of the 24 $\mu m$ emission suggests that these larger grains in the immediate vicinity of the O stars are blown away by the strong stellar winds.

3.3. Spatial Variation in SED Types

Class I and II objects are present in varying amounts across W5. Although with our present data set we cannot tell if any one Class I object is younger than a given Class II object, these classes do represent different evolutionary stages in the formation

| Object | R.A.(J2000.0) | Decl. (J2000.0) | Type   |
|--------|--------------|----------------|--------|
| 1      | 2 49 55.78   | 60 26 24.46    | Comet  |
| 2      | 2 50 28.16   | 60 09 30.44    | Comet  |
| 3      | 2 50 33.85   | 60 25 47.12    | Comet  |
| 4      | 2 51 32.90   | 60 03 53.34    | Trunk  |
| 5      | 2 51 53.91   | 60 06 56.97    | Comet  |
| 6      | 2 52 17.19   | 60 03 17.22    | Trunk  |
| 7      | 2 52 21.75   | 60 54 11.86    | Trunk  |
| 8      | 2 53 39.14   | 60 46 50.51    | Trunk  |
| 9      | 2 53 39.22   | 60 30 17.95    | Comet  |
| 10     | 2 54 52.34   | 60 35 43.16    | Trunk  |
| 11     | 2 54 58.35   | 60 41 43.76    | Trunk  |
| 12     | 2 56 8.69    | 60 10 25.26    | Trunk  |
| 13     | 2 58 37.57   | 60 41 53.69    | Comet  |
| 14     | 2 59 46.22   | 60 21 10.32    | Comet  |
| 15     | 3 0 23.53    | 60 17 55.05    | Trunk  |
| 16     | 3 1 1.98     | 60 21 57.54    | Trunk  |
| 17     | 3 1 17.47    | 60 24 13.20    | Trunk  |
| 18     | 3 1 47.94    | 60 35 24.03    | Trunk  |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
of stars. In W5 we find that in regions where our $^{12}$CO emission map exceeds $T_K = 7.5$ K km s$^{-1}$, there are on average 0.23 Class I objects for every Class II. In regions with $T_K < 7.5$ K km s$^{-1}$, the ratio is 0.04. This suggests that the stellar clusters associated with significant molecular material in W5 are systematically younger than those in cleared out regions, for example the H ii region cavities.

The varying levels of completeness in each IRAC map as a function of association with the bright, diffuse emission affect our result. As described in § 2, the 90% limiting magnitude decreases by $\sim$1.5 mag in IRAC channels 1 and 2, by $\sim$2.5 mag in channel 3 and by $\sim$3.2 mag in channel 4 in going from the evacuated H ii region to the brightest regions of diffuse emission. Recently, Chavarría et al. (2008) studied the effects of reduced sensitivity in the 5.8 and 8 $\mu$m Spitzer bands, combined with the obscuring effect of bright, diffuse PAH emission on the detection of Class I and Class II sources in IRAC surveys. They found that Class II sources are on average fainter than Class I’s and are likely preferentially missed in bright PAH emission regions as a result.

3.4. Clustered versus Distributed Star Formation in W5

We want to describe in an objective way how the stars in W5 are grouped, as well as address the following question: is there a population of stars that do not belong to identifiable groups that may have formed in isolation, in other words, a “distributed” population? Lacking a data set that describes the masses and dynamics of the stars and gas which would allow us to assign stars to clusters based on gravitational association, we base cluster membership only on spatial arrangement on the sky and so we do not require that these clusters be gravitationally bound. We restrict ourselves to infrared excess sources only to simplify the issue of whether stars are associated with W5. We include the deeply embedded sources and transition disk candidates along with the Class I and Class II objects and exclude stars exhibiting only photospheric emission (Class III sources) and AGN and PAH galaxies, for a total of 2064 objects. The source distribution is shown in Figure 7 and reproduced in Figure 9 without the background image.

Determining a criterion for cluster membership from spatial distributions alone is somewhat arbitrary. In this paper we use the so-called minimal spanning tree (MST) method to identify and characterize clustering in W5 (see recent work by Cartwright & Whitworth 2004; Bastian et al. 2007). Gower & Ross (1969) describe how such a tree is constructed from a list of source positions. To construct the tree, we first generate the network of lines that joins together the positions of all objects in our input list, such that the total length of all lines joining points is minimized and there are no closed loops. Each object is assigned one “branch length,” that is, the projected distance to its nearest neighbor. We plot the distribution of branch lengths in Figure 10.

Distinguishing clustered from distributed objects using the MST requires two things: a break/cutoff length, $d_b$, and a minimum group size, $N$. A group is then a collection of objects linked by branches shorter than $d_b$ with at least $N$ stars (we choose $N = 10$). We can estimate a value for $d_b$ from the distribution of branch lengths in Figure 10. Following Gutermuth et al. (2008b), we fit straight lines through the long- and short-length portions of the distribution. Where these lines cross defines the break length for clustering. For the IR excess sources in W5 this method yields $d_b = 0.86$ pc. Using this break length we find 16 groups containing at least 10 stars and a clustered fraction of 70%.

![Figure 9](image_url) Distribution of stellar sources as in Fig. 7. Green points: Class II; red: Class I; yellow: transition disk candidates. Black asterisks mark the location of the known O stars.

![Figure 10](image_url) MST length distribution, showing each object’s branch length (y-axis) vs. its number in the sorted list. Straight line fits (dashed lines) to the short- and long-length parts of the distribution intersect at 0.86 pc.

![Figure 11](image_url) MST results. Solid line and left y-scale: Clustered fraction of stars (belonging to all groups $\geq$ 10 stars) as a function of branch length cutoff. Dashed line and right y-scale: Number of groups ($N_{grp}$) containing 10 or more stars identified by the MST algorithm. Note: The coarse steps on the x-axis miss the finer detail in $N_{grp}$; the true peak is 27 groups at $d_b = 0.54$ pc.
A single value of $d_s$ chosen in this way may not be representative of the varying spatial density of stars across the region and may underestimate the amount of substructure within groups. Altering $d_s$ changes the number of groups and the relative fraction of clustered and distributed sources. As the cutoff length is increased, an increasing fraction of objects qualify as clustered. The number of groups ($N_{\text{grp}}$) we find also increases up to a maximum before falling off as groups start to merge, until all groups belong to a single cluster. These trends are shown in Figure 11. An alternate value for the break length $d_s$ can be derived from the peak in the plot of $N_{\text{grp}}$ versus increasing $d_s$. As argued by Battinelli (1991), this method can be thought of as returning a maximum of information from our source distribution. In this case we find a cutoff of $d_s = 0.54$ pc, $N_{\text{grp}} = 27$, and a clustered fraction of 44.2%. In Figure 12 we compare the groupings produced by the two methods side by side to demonstrate this finding.

Both values of $d_s$ used here are large when compared to the typical separations of stars in nearby regions such as Taurus (Hartmann et al. 2005), where a cutoff length of 0.54 pc would incorporate many objects not associated with any cluster. However, Taurus is a low-mass star-forming region and so the characteristic scales of clustering are likely to be smaller there. In recent surveys of low-mass star-forming regions (Enoch et al. 2007) and the high-mass star-forming regions in Cygnus (Motte et al. 2007), typical star-forming dense cores are $\sim 0.1$ pc in size. However, Motte et al. (2007) also found that massive dense clumps can be much larger, 0.5–0.8 pc, which may be a more relevant scale for cluster and massive star formation than for low-density, more isolated star formation seen in Taurus.

Table 5 summarizes the clustering results from the two methods. The value for the fraction of stars in clusters from both these methods is lower than that reported by Allen et al. (2007) in Spitzer surveys of Orion and Ophiuchus (74%–78%). Carpenter (2000), in his analysis of the Orion A and B, Mon R2, and Perseus molecular clouds with 2MASS, found a range of clustering fractions, different for every cloud, between 56%–100%. This fraction could be as much as a factor 2 lower, depending on how the age of the distributed population is modeled. In W5—at a distance of 2 kpc—we are sampling much less of the IMF than in these nearby regions, which lie within 1 kpc of the Sun. We also do not know the disk-fraction of YSOs in the W5 clusters. Cieza et al. (2007) have shown that a significant fraction of stars lose detectable circumstellar disks (in the mid-IR) on a timescale $\sim 1$ Myr. These objects would not be included in our sample of IR-excess sources.

The mass completeness limit for our survey is dictated by our photometric completeness and the wide span of YSO mid-IR colors. The primary constraint in completeness for the IRAC four-band sample is the 8 $\mu$m detection limit, since this has low sensitivity and very bright background contamination from PAH feature emission. A typical photosphere, with $[3.6] - [8.0] \sim 0.1$ at age 2 Myr and $[8.0] = 12.7$, equates to a limiting mass $\sim 2 M_\odot$ (using the evolutionary models of D’Antona & Mazzitelli [1994] and adopting $A_V = 2$, a typical value for the H ii region cavity; Hillwig et al. [2006]). On the bright diffuse emission the 8 $\mu$m detection limit for a photosphere equates to $\sim 8 M_\odot$. The additional 2MASS+IRAC bands 1 and 2 sample is limited by the $K_s$-band completeness. We estimate that the 90% completeness in this band is 14.2. Using the models of Baraffe et al. (1998) this equates to a star of $1 M_\odot$ at 2–2.5 Myr, at an $A_V$ of 2 and a distance of 2 kpc. Both the 8 $\mu$m and $K_s$-band mass completeness limits are conservative estimates, since YSOs with infrared excess emission will be detected more readily. For example, the $[3.6] - [8.0]$ color peaks at $\sim 1.4$ for IR excess YSOs in W5. In this case $[8.0] = 12.7$ converts to a mass of $\sim 0.8 M_\odot$ at 2 Myr in the cavity. In summary, we estimate that for a young population of 2 Myr age, we are complete to $\sim 8 M_\odot$ for photospheres and $\sim 4 M_\odot$ for typical disk excess objects in the IRAC four-band sample seen against the bright background. In the cavity we are complete to $\sim 2 M_\odot$ for photospheres and $\sim 0.8 M_\odot$ for disk excess objects. In the additional 2MASS sample we are complete to a mass $\sim 1 M_\odot$.

**Table 5: Clusters/Groups in W5**

| Parameter                        | Method                  |
|----------------------------------|-------------------------|
| Total $N_c$ in clusters          | Straight-Line Fit        |
| 1444                             |
| Group size ($N_c$)               | $N_{\text{grp}}$        |
| 10–459                           |
| Percent in clusters              |                         |
| 70.0                             |
| $N_c/N_{\text{tot}}$ (%)         | 0–50                    |
| 0–50                             |                         |
4. DISCUSSION

4.1. Origin of the Distributed Population

Our clustering analysis shows that there is a significant distributed population of young stars (30%–57% of IR excess objects). These may have formed in groups or clusters and dispersed through random motions or been ejected at high velocity. Conversely, they may have formed in their current locations in largely unrelated, isolated events.

On a ~10 Myr timescale, the distributed population may be a natural consequence of dynamical interactions between young stars in groups throughout the original giant molecular cloud. Small groups (N < 36) have short relaxation times relative to their crossing times and, once the gas is removed, will not remain visible as clusters for much longer than this (Adams & Myers 2001). However, if we assume that the distributed stars are only as old as the oldest O star in W5 (a reasonable assumption, given that we have identified them through their IR excess emission), they will have had <5 Myr to travel.

Extreme dynamical interactions, namely, close encounters between stars in multiple systems, can produce high-velocity runaway stars. Numerical studies show that a group of stars will eject a member within about 100 crossing times (~30,000 yr; Reipurth 2000). Sterzik & Durisen (1995) calculate similar timescales for close systems consisting of five stars and predict velocities of 3–4 km s−1 for the ejected stars. Few have been found; Goodman & Arce (2004) find seven high-velocity (>10 km s−1) candidates in the literature.

Forés et al. (2006, 2008) measured the radial velocities of young stars in NGC 2264 and the Orion Nebula cluster, and found dispersions of 3.5 and 3.1 km s−1, respectively. In W5 the average projected distance of distributed stars from the nearest cluster is 8.5 pc. Assuming a velocity of 3 km s−1 perpendicular to the line of sight, this distance could be traversed in ~3 Myr—well within the current upper age limit for W5 (5 Myr; see Karr & Martin 2003). Thus, it is plausible that at least some of the distributed population originated in nearby clusters.

4.2. Star Formation Efficiency

We calculate the star formation efficiency in W5 using the equation

$$\epsilon = \frac{M_{\text{stars}}}{M_{\text{gas}} + M_{\text{stars}}}.$$ (2)

Here $M_{\text{stars}}$ represents the mass in young stars only, as identified by their infrared excess, so $\epsilon$ is a current efficiency, averaged over the last few million years. For the entire W5 region we count 2064 young stars and assume an average mass of 1 $M_\odot$. To find the gas mass we use the $A_\nu$ map of W5 described in § 3.1 and estimate the molecular gas column density from the standard relation: $N(H_2) = 1.9 \times 10^{21} A_\nu$ protons cm−2 (see, for example, Bohlin et al. 1978). Assuming that all gas is associated with W5, we convert $N(H_2)$ to a projected two-dimensional mass density at each pixel in the $A_\nu$ map: $\kappa = 15 \times A_\nu$, pc−2 (as in Lombardi & Alves 2001). Each $A_\nu$ map pixel has a size 0.34 × 0.34 pc. Over our whole survey field, we find a total gas mass of 6.5 $10^6 M_\odot$ and derive an efficiency of 3%.

We calculate $\epsilon$ for the clusters identified by our MST treatment in § 3.4. For each of the 16 clusters, we count the number of stars contained, assume a stellar mass of 1 $M_\odot$, and add up the gas in the corresponding pixels. Inside the H ii region cavity, where the molecular gas has been destroyed, the efficiencies are high (26%–39%). In the rim of W5, where molecular gas remains and embedded clusters are found, $\epsilon$ is 10%–17%. These latter values are likely a lower limit, as our census of young stars is incomplete in the bright extended emission coincident with the embedded clusters.

Recent results from the c2d survey (N. J. Evans II et al. 2008, in preparation) show that nearby dark clouds where low-mass star formation is occurring have star formation efficiencies of 2%–4% cloud-wide and 15%–20% in clusters, similar to the values we have obtained for the high-mass star-forming region W5. Our results for $\epsilon$ in the clusters are also comparable to those of Chavarría et al. (2008) for the S255 region.

4.3. Triggered Star Formation in W5

We consider two mechanisms of triggered star formation relevant to W5. The first mechanism, called radiatively driven implosion (VDI), is the compression of preexisting density enhancements (small cloud clumps or globules) inside and on the boundary of the ionized bubble by the high pressure of the H ii region (for a review, see Klein et al. 1985). Clumps of material visible as bright PAH emission in IRAC bands 1, 3, and 4 with spatially coincident Class I or Class II objects are summarized in Table 4. These include isolated clumps, elephant trunk formations, and bright rims (as shown in Fig. 8). As discussed in Elmegreen (1998), if globule squeezing does occur, its timescale is expected to be short, since an isolated overdensity can be compressed immediately on being engulfed by the H ii region or stellar wind. Thompson et al. (2004) investigated the cometary features on the southern rim of W5 West for signs of star formation triggered via the RDI mechanism (globules 4–6 in our Table 4). They found that the Hα, CO-molecular, and dust morphologies of the three pillars are “reasonably consistent” with the model of Lefloch & Lazareff (1994) for radiatively driven implosion at the early collapse phase. They used near-IR photometry to detect several candidate young stellar objects—these we confirm through our Spitzer photometry as Class I and Class II objects. They estimate that the timescales for duration of UV illumination, shock crossing times across the features, and protostar/YSO ages are all ~105 yr. Since Thompson et al. (2004) were only able to establish that approximate pressure equilibrium holds in the pillar heads from their data, we need a more detailed study of the gas dynamics in these pillars to determine if they are currently collapsing due to external pressure from the H ii region.

The second mechanism, collect-and-collapse, is the large-scale expansion of an ionized bubble, powered by an overpressurized H ii region and stellar winds. This expansion can drive shock fronts into the surrounding medium, sweeping up a dense ridge or shell which collapses into stars when a critical density of material accumulates. Whitworth et al. (1994) presented an analytical treatment of this process. A shock front forms and gathers material until it is able to fragment and collapse to form stars, at a time $t_{\text{frag}}$ and radius $R_{\text{frag}}$ given by

$$t_{\text{frag}} = 1.56 \text{ Myr } a_0^{7/11} L_{49}^{-1/11} n_3^{-5/11},$$ (3)

$$R_{\text{frag}} = 5.8 \text{ pc } a_0^{4/11} L_{49}^{-1/11} n_3^{-6/11},$$ (4)

where $a_0$ is the sound speed inside the shocked layer in units of 0.2 km s−1, $L_{49}$ is the central source ionizing flux in units of 1049 photons s−1, and $n_3$ is the initial gas atomic number density in units of 103 cm−3. 


In any massive star-forming region, presumably some combination of H II region expansion and stellar-wind forces operate. Stellar winds certainly play a significant role in shaping the morphology of an H II region only until an age of \( \sim 10^5 \) yr. As shown by McKee et al. (1984) and Weaver et al. (1977), weak stellar winds (wind luminosity \( \ll 1.26 \times 10^{36} \times L_{49} \times n \), where \( n \) is the ambient density) are likely to be confined by the H II region pressure to a smaller bubble around the ionizing source, since gas that is evaporated from clumps of material in the H II region mixes with the hot stellar wind bubble and can radiate energy away efficiently. Strong winds can overcome this confinement—they create a bubble with size determined by the photoevaporation and displacement of surrounding inhomogeneities in the ambient gas. This then expands along with the H II region. In estimating the lifetimes of the W5 bubbles, we thus consider only the effects of the H II region expansion.

As described in §1, the gross morphology of W5 in the mid-IR is defined by two large, roughly circular rings of bright PAH emission that mark the smaller W5 East (W5E, radius \( \sim 10 \) pc) and larger, more irregular W5 West (W5W, overall radius \( \sim 22 \) pc). At the approximate center of W5E lies HD 18326, an O7 V star surrounded by a dense cluster of young stars. It seems reasonable to assume, whether this is a sphere or a ring of gas, that the cluster lies near the true center and is not significantly offset either to the foreground or background. Adopting stellar parameters from Martins et al. (2005) an O7 V star will have ionizing flux \( L_{49} = 0.43 \). Since we cannot calculate appropriate values for \( a_{0.2} \) and \( n_1 \) from our current data sets, we adopt 1.0 for both. The H II region fragmentation time we calculate is 1.69 Myr at a radius of 5.37 pc. Both Whitworth et al. (1994) and Dale et al. (2007) note that the density in a real region is likely to be lower—this would make the fragmentation time longer and the radius larger by a factor \( \sim 2 \).

W5W presents a less clear-cut picture. It contains an isolated O8 V star, HD 237019, as well as three dense clusters centered on BD \(+60 586\) (O7.5 V), and the multiple systems HD 17505 [two O7.5 V((f)) stars, an O6.5 III((f)), and an O8.5 V] and HD 17520 (O9 V+Be). See Hillwig et al. (2006) for a more detailed study of the O stars in W5. The relative configuration of these four systems and their relationship to the surrounding diffuse gas (whether in front or behind) is not known. We consider here two simple scenarios and assume that all four objects and the ring of PAH emission are in the same plane. Scenario 1: HD 237019 represents an initial episode of star formation, and its isolation is due to its cluster having had time to disperse. In the Whitworth model, an O8 V star has a fragmentation time of 1.8 Myr and collapse of swept-up gas occurs at a radius of 5.0 pc. In this picture this event triggered the formation of the three dense clusters in W5W which all lie at roughly 6.8 pc from HD 237019. These clusters, and the continuing expansion of the H II region, then triggered the current, ongoing star formation seen in association with molecular clouds W5NW and W5NE. Scenario 2: the three dense clusters form together—with their present arclike arrangement due to some initial filamentary distribution of molecular material. They then trigger star formation in the remaining molecular material to the north, northeast, and south. The O7.5 V star BD \(+60 586\) by itself has a fragmentation time of 1.75 Myr and collapse occurs at a radius of 5.16 pc. The combined systems HD 17505 and HD 17520 (with at least five O stars; see Hillwig et al. 2006) have a fragmentation time of 1.46 Myr and collapse occurs at a radius of 6.19 pc. In this picture HD 237019 would have been ejected from one of the multiple O star systems. Located at \( \sim 10 \) pc from the nearest cluster, assuming a velocity entirely transverse to our line of sight of 10 km s\(^{-1}\), it would take \( \sim 1 \) Myr to arrive at its current location, consistent with the likely young age of the cluster as a whole. Moffat et al. (1998) found a runaway frequency percentage of 14% among Galactic O stars and included this star as a marginal runaway candidate. Although the most favored creation mechanism for runaways is supernova ejection (Blauuw 1961), ejection from compact young stellar clusters or through binary interaction is also thought to be responsible for some O star runaways (Poveda et al. 1967; Clarke & Pringle 1992). Moffat et al. (1998) found HD 237019 to be only a marginal runaway candidate, given the large uncertainty in its tangential velocity, 15 \( \pm 17 \) pc Myr\(^{-1}\).

There are several observations consistent with the collect-and-collapse mechanism in W5. The low level of nonthermal radio emission suggests that there have been no supernovae during its lifetime (Vallée et al. 1979). The main-sequence lifetimes of the O stars are estimated to be \( < 5 \) Myr (Karr \\& Martin 2003). The timescales for triggering presented above are shorter than this. Wilking et al. (1984) found several young embedded OB stars around W5 in the molecular clouds and argued that their locations near to the cloud edge, together with some evidence of magnetic field alignment parallel to the ionization front are suggestive of triggering via external compression. Finally, Nakano et al. (2008) found evidence of an age difference of \( \sim 3 \) Myr between the cluster around HD 18326 in the W5 East bubble and the young stars in the rim. This is longer than our estimate above of \( \sim 1 \) Myr, but given the uncertainties in gas sound speed \( a \) and initial cloud number density \( n \), it is an allowable timescale in the collect-and-collapse model.

Karr \\& Martin (2003) argue that the distribution of young stars in W5 indicates a shorter timescale, more consistent with RDI than with collect-and-collapse. They investigated the locations of IRAS point sources with colors corresponding to YSOs. Their results did suggest a two-generation model, with older stars at the centers of the H II regions and ongoing star formation surrounding them; however, they found that the number density of young objects peaks \( \sim 5 \) pc inside the H II region (as defined by the 6.2K 1420 MHz contour), which corresponds to a triggering timescale of 0.5–1 Myr. Of the 42 IRAS sources from their list that fall within our Spitzer image, we find only 16 in our source list at 24 \( \mu \)m. The remainder may be spurious (they are also not seen in our 70 \( \mu \)m image) and in fact may be small knots of IR emission that masquerade as point sources in the IRAS survey. All are associated with bright PAH emission, including one coincident with globule 8 in Table 4. The peak in IRAS-classified YSOs found by Karr \\& Martin (2003) is also not upheld by an analysis of our Spitzer sample, which shows that the Class I objects are found predominantly along the cloud rims or at the cloud centers. This distribution, with the YSOs further from the O stars argues for the longer timescale of collect-and-collapse.

Studies of a young embedded object G138.295+1.555 and the UCH II region G138.300+1.558 in AFGL4029 (W5E) with near- and mid-IR imaging (Deharveng et al. 1997; Zavagno et al. 1999) suggest that collect-and-collapse is not playing a role in star formation here, since the youngest object (the former) is apparently closer to the ionization front than the older, latter object. However, the true three-dimensional configuration of all the objects involved is not exactly known, this may be due to projection effects. The clustering of Class II objects immediately outside the cloud to the west of G138.295+1.555 and G138.300+1.558 certainly suggests that the sequence of star formation here is west to east, i.e., outside-in, away from the ionizing star HD 18326.
Considering our simple model and the results in the literature, it seems plausible that both the RDI and collect-and-collapse mechanisms are at work in W5: RDI on the smaller scale of cometary globules and collect-and-collapse on the larger scale of the H\textsc{ii} region. Detailed investigations (X. P. Koenig et al. 2008, in preparation) of the spatial distributions and relative ages of the YSOs may further constrain the scenarios presented here.

5. CONCLUSIONS AND FUTURE WORK

We have presented initial results from our extensive Spitzer survey of W5. Shorter wavelength data from IRAC (3–8 $\mu$m) and longer (24 $\mu$m) wavelength data from the MIPS instrument were combined to maximize spectral coverage of detected sources.

Even before photometric analysis, dense clusters of stars are clearly visible across the region, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520, and also across the region, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520, and also across the region, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520, and also across the region, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520, and also across the region, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520, and also across the region, centered on the O stars HD 18326, BD +60 586, HD 17505, and HD 17520. At 24 $\mu$m, substantial extended emission is visible, presumably from heated dust that survives in the strongly ionizing environment of the H\textsc{ii} region.

We used photometry of more than 18,000 point sources to analyze the spatial distributions of young stars, establish their evolutionary status via their infrared colors and magnitudes, and assess their clustering properties across this large star-forming region. The large clusters that dominate the region, centered on the massive O stars, contain numerous infrared excess sources. Looking at the large-scale distributions of stars at different evolutionary stages, we find that within the evacuated cavity of the H\textsc{ii} regions, the ratio of Class II (older) to Class I (younger) sources is $\sim$7 times higher than for objects detected coincident with the molecular clouds in the rim. We attribute this difference to an age difference between the two locations, and consequently postulate that at least two distinct generations of star formation are visible in the region. An isolated O star in W5 West, HD 237019, may represent an initial episode of star formation in the region, preceding the formation of the large clusters in the cavity, although we cannot rule out its ejection from an O star multiple system, for example, HD 17505.

The clustering results show that, considering infrared excess sources alone (2064 objects), $\sim$45%–70% are found in clusters with $\geq$10 members. Incorporating the sources apparently misclassified as AGN and PAH galaxies (see the Appendix) extends this range to $\sim$40%–70%. The remainder are in the distributed mode, many of which could have formed in nearby clusters.

We looked at the role that triggered star formation may have played in W5. We cataloged isolated globules of diffuse PAH emission, and so-called elephant trunk structures that contain young protostars or stars with protostellar disks. These are examples of possible RDI-triggered star formation events. On the larger scale, we tested the analytical formulations of Whitworth et al. (1994) for the collect-and-collapse mechanism. Our simple estimates show that triggering remains a plausible mechanism to explain the multiple generations of star formation in W5 and merits further investigation.

Substantial work is ongoing to refine our understanding of star formation in W5 in the light of triggering models and the clustering of stars. We have undertaken a near-infrared survey of the whole region in $J$, $H$, and $K_S$ bands to extend the stellar SEDs to shorter wavelengths and detect more young stars against the bright background emission in W5. This will permit a full analysis of the clustering of young stars in the region. We have obtained optical spectra of several hundred stars across W5 with the aim of determining their relative ages by constructing Hertzsprung-Russell diagrams. This will allow us to better understand the history of star formation across the entire region. A much clearer picture of the progression of star formation across W5 and the role of feedback in this process should result.

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Facilities: FLWO:2MASS, Spitzer

APPENDIX

AGN/PAH GALAXY FILTERING

Following Gutermuth et al. (2008a), PAH galaxy candidates are identified on the basis of the following criteria:

\[
\begin{align*}
[4.5] - [5.8] &< \frac{1.05}{1.2} (5.8) - [8.0] - 1), \\
[4.5] - [5.8] &< 1.05, \\
[5.8] - [8.0] &> 1, \\
[3.6] - [5.8] &< \frac{1.5}{2} (4.5) - [8.0] - 1), \\
[3.6] - [5.8] &< 1.5, \\
[4.5] - [8.0] &> 1.
\end{align*}
\]
After removing these sources, AGNs are then picked out following these criteria:

\[
\begin{align*}
[4.5] - [5.8] & > 0.5, \\
[4.5] & > 13.5 + (4.5 - [8.0] - 2.3)/0.4, \\
[4.5] & > 13.5.
\end{align*}
\]

We plot the distribution of 729 AGN and 198 PAH galaxy candidates in W5 in Figure 13. It is notable that these objects show obvious nonuniformity. The nonuniformity arises from several sources: (1) variation in the intrinsic distribution of galaxies toward (behind) W5, (2) variable extinction across the region due to the molecular clouds that make up W5 and material along the line of sight through the Galaxy in this direction, (3) variable levels of photometric completeness across the field due to bright extended nebular emission, and (4) clustering coincident with the positions of the dense clusters of young stars around the O stars in the W5 H II region cavity, due to faint (low mass) stars misclassified as AGN or PAH galaxies. This last issue affects all of our analysis, and thus we need to characterize—statistically—the properties of these misclassified objects and how adding them back to the original sample affects our previous results.

We consider the AGNs first. In the extreme case, in which all objects are misclassified, we return the full list of 729 AGNs to the stellar list, classify the returned objects into Class I, II, etc., and examine the clustering fraction. With the MST straight-line fit method, we find \(d_s = 0.88\) pc, \(N_{grp} = 21\), and a clustered fraction = 68.6%. If we use the maximum in the \(N_{grp}\) distribution we find \(d_s = 0.5\) pc, \(N_{grp} = 26\), and a clustered fraction = 40.4%.

Alternatively, presumably some intermediate fraction of AGNs should be returned as AGNs. We must first calculate the expected number and averaged distribution of AGNs in W5 using a sample of AGNs extracted by Stern et al. (2005) from the Spitzer IRAC shallow survey of the Boötes field (Eisenhardt et al. 2004), convolved with our extinction map (as described in \(\S\) 3.1) and with completeness estimates derived for our Spitzer survey of W5 via a simple Monte Carlo simulation code. The model AGN sample is drawn from a 7.7 deg² section of the Stern et al. (2005) survey, identifying sources as AGNs based on the same color classification scheme that we use in this paper (Gutermuth et al. 2008a).

We use the IRAC completeness maps as described in \(\S\) 3.1. The area imaged in our W5 survey (3.5 deg²) is smaller than that covered by the Boötes data. In our Monte Carlo simulation we input a proportionately smaller, random selection of AGNs from the Boötes list and distribute these randomly in the field of W5. Each object is assigned an \(A_V\) value based on its location in the extinction map. We apply this extinction to its IRAC photometry using the infrared extinction relation presented in Flaherty et al. (2007). The corresponding location within the completeness maps gives us the completeness value (a number \(\leq 1\)) at each of the four IRAC wavelengths, given its extincted magnitude. A random number generator is then used to determine whether or not an object is detected, with the completeness estimates as a measure of the probability of detection. For detection we require that an object be detected in all four IRAC bands. This simulation predicts on average 270 AGNs detected in W5.

This distribution of AGNs has a certain characteristic space density distribution. At each iteration we measure the nearest neighbor distance distribution (Casertano & Hut 1985). For each object we find the projected distance to its sixth nearest neighbor in arcseconds \((d_p)\) and construct a histogram of distances. The final output of the code is an averaged histogram combining 1000 outcomes of the simulation. For comparison, we generate the distribution of \(d_p\) for the real AGN candidates in W5 and compare the results in Figure 14 (leftmost panel). In the two panels to the right we compare the output magnitude and color distributions of the simulated AGN (averaged over 1000 outcomes) with our W5 AGN candidates.

These distributions can be used to generate a probability that an object in our AGN list of given \(d_p\), [4.5] mag, and [4.5] - [8.0] color is a YSO. In Table 6 we present the source properties of the 729 W5 AGN candidates. Each object is listed with its coordinates and photometry in 2MASS and Spitzer bands, and given a combined \(P(YSO)\) value, that is, the probability given its local surface density, [4.5] mag and [4.5] - [8.0] color.

We statistically return a sample of AGNs to the YSO list based on these probabilities to test the effect on the clustered fraction. We run our
MST clustering analysis on the resulting list of YSOs plus YSO-AGNs. In Table 7 we show the averaged results of adding AGNs back to the YSO sample according to the different filters and compare to the original YSO-only sample result.

The space density filter typically returns \( \frac{C_25}{C25} \approx 460 \) objects to the list. The combined filter returns \( \frac{C24}{C24} \approx 230 \). Although a significant fraction of objects that are returned from AGNs to YSOs join the clustered population, many are added to the distributed sources, which increases the fraction outside groups and clusters.

**TABLE 6**

| ID   | R.A. (deg) | Decl. (deg) | J (mag) | H (mag) | Ks (mag) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) | [24] (mag) | Type \( a \) | \( P(YSO) \) \( b \) |
|------|------------|-------------|---------|---------|----------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|
| g1   | 41.176602  | 60.672605   | ...     | ...     | ...      | 15.52(03)   | 14.62(03)   | 14.71(17)   | 13.28(18)   | ...         | PAH          | 0.00         |
| g2   | 41.189968  | 60.652874   | ...     | ...     | ...      | 15.17(03)   | 14.48(04)   | 14.07(11)   | 13.02(11)   | ...         | AGN          | 0.28         |
| g3   | 41.190158  | 60.586695   | 17.00(19)| ...     | ...      | 14.04(01)   | 13.65(02)   | 12.98(06)   | 11.99(07)   | ...         | AGN          | 0.22         |
| g4   | 41.242231  | 60.703623   | ...     | ...     | ...      | 14.72(03)   | 13.85(04)   | 13.31(12)   | 12.19(17)   | ...         | AGN          | 0.05         |
| g5   | 41.245464  | 60.731615   | ...     | ...     | ...      | 14.71(03)   | 13.93(03)   | 13.35(08)   | 12.38(07)   | ...         | AGN          | 0.10         |
| g6   | 41.252453  | 60.541187   | ...     | ...     | ...      | 14.53(03)   | 13.97(02)   | 13.48(07)   | 12.37(06)   | ...         | AGN          | 0.37         |
| g7   | 41.256135  | 60.465426   | 14.27(04)| 13.83(04)| 13.62(04)| 13.47(01)   | 13.51(02)   | 13.57(08)   | 11.77(03)   | ...         | PAH          | 0.02         |
| g8   | 41.274375  | 60.732626   | 16.90(17)| 16.23(24)| 15.34(15)| 14.65(03)   | 14.15(03)   | 13.71(12)   | 11.95(08)   | ...         | PAH          | 0.00         |
| g9   | 41.293823  | 60.525857   | 15.26(05)| 14.61(06)| 14.55(08)| 14.36(01)   | 14.32(03)   | 14.25(12)   | 13.69(18)   | ...         | AGN          | 0.63         |
| g10  | 41.294108  | 60.520992   | ...     | ...     | ...      | 15.30(03)   | 14.64(03)   | 13.96(09)   | 12.96(09)   | ...         | AGN          | 0.40         |

**Notes**—Table 6 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

Values in parentheses signify error in last two digits of magnitude value. Right ascension and Declination coordinates are J2000.0.

\( a \) Galaxy type: AGN or PAH galaxy as defined in text.

\( b \) Probability that source is a YSO based on local space density, color, magnitude criteria; see text.
The objects returned to the stellar sample will also affect the Class I/Class II ratio. Applying the density filter returns a sample with ~16% Class I objects and the remainder Class II. If we apply the combined filter, typically 4% are Class I and 96% Class II. The effect on the ratio test is small: we increase the proportion of Class I objects in the H II cavity from 4% to ~7%. The fraction associated with the molecular gas remains at 23%, and thus our earlier result and conclusion still holds. A summary of the results of these results is given in Table 7.

For the smaller sample of PAH galaxies, statistical analysis carried out as above predicted on average 211 objects. However, we find 198 candidate PAH galaxies in W5, of which certainly some fraction are stellar objects, as can be seen from the nonuniformity in Figure 13. Although our model predicts an excess of PAH galaxies over those detected, we can still use the same procedure for these objects as for the AGNs to generate a probability, $P(YSO)$, based on colors and space density. We present the 198 PAH galaxy candidates in Table 6 along with the AGNs with the same format of coordinates and photometry. We provide a $P(YSO)$ value for each, derived from local space density and [3.6] – [5.8] and [4.5] – [8.0] colors.

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### Table 7

| FILTER | MST STRAIGHT-LINE FIT | MST N_{gpp}^d, MAXIMUM |
|--------|------------------------|------------------------|
|        | Clustered (%) | $d_c$ (pc) | $N_{gpp}$ | Clustered (%) | $d_c$ (pc) | $N_{gpp}$ |
| Space density | 66.0 | 0.8 | 19 | 43.4 | 0.5 | 26 |
| Combined | 68.0 | 0.8 | 17 | 45.5 | 0.5 | 25 |
| No AGN | 70.0 | 0.86 | 16 | 44.2 | 0.54 | 27 |
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