Regularly Spaced Infrared Peaks in the Dusty Spirals of Messier 100

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Abstract

Spitzer Space Telescope Infrared Array Camera (IRAC) images of M100 show numerous long filaments with regularly spaced clumps, suggesting the associated cloud complexes formed by large-scale gravitational instabilities in shocked and accumulated gas. Optical images give no hint of this underlying regularity. The typical spacing between near-infrared clumps is ~410 pc, which is ~3 times the clump diameter, consistent with the fastest growing mode in a filament of critical line density. The IRAC magnitudes and colors of several hundred clumps are measured in the most obvious 27 filaments and elsewhere. The clump colors suggest that the dust is associated with diffuse gas, polycyclic aromatic hydrocarbon emission, and local heating from star formation. Neighboring clumps on the same filament have similar magnitudes. The existence of many clumps all along the filament lengths suggests that the ages of the filaments are uniform. The observations support a model where interstellar gas is systematically accumulated over lengths exceeding several kpc, forming spiral-like filaments that spontaneously collapse into giant clouds and stellar complexes. Optical wavelengths show primarily the irregular dust debris, H II regions, and lingering star formation downstream from these primal formation sites.

Key words: galaxies: ISM – galaxies: spiral – galaxies: star formation – ISM: structure – stars: formation

Supporting material: machine-readable tables

1. Introduction

Local star formation is often in small filaments that form from transverse compression and then gravitationally collapse in a semiregular fashion into cores (e.g., André et al. 2010; Miettinen 2018). Sometimes these cores are at the intersections of several filaments (Myers 2009). Also on a galactic scale, stars form in filaments that may be shock fronts in spiral arms (e.g., Goodman et al. 2014; Ragan et al. 2014) or rings from the expansion of superbubbles (Egorov et al. 2017). Optical observations of galactic-scale star formation is confusing, however, because extinction, irregular morphologies of star complexes, and Hα emission that is offset from the gas can make the intrinsic regularities of filament collapse look more chaotic than it is.

Baade (1963) commented that in spiral galaxies, bright stars are “strung out like pearls along the arms.” Early theoretical work considered shock compression (Roberts 1969, p. 63) and phase transitions (Shu et al. 1972) as a way to enhance gas self-gravity and star formation in the arms. Mouschovias et al. (1974) explained the regular spacing of star formation with a magnetic Rayleigh–Taylor instability. Star formation triggered by enhanced cloud collisions in the arms may also be involved (Kwan & Valdes 1983; Scoville et al. 1986), and even cloud collisions can give a regular spacing because of epicyclic motions (Dobbs 2008).

To study the regularity of spiral arm star formation in more detail, Elmegreen & Elmegreen (1983) selected 22 galaxies with some evidence for regularity in the optical images and measured the average ratio of the separations to the sizes of the star-forming regions, obtaining a value of 3.1 ± 1.2. They suggested that the regions formed by gravitational instabilities at the Jeans length for the average gas density and velocity dispersion in the arms. Regularly spaced star-forming clumps were observed more clearly in the spiral arm filaments of the interacting galaxies NGC 2207 and IC 2163 (Elmegreen et al. 2006), where a characteristic luminosity rather than the usual power-law luminosity function was inferred for the regions in the brightest arm. Efremov (2010) measured the properties of regularly spaced star formation in M31, and Gusev & Efremov (2013) observed it in NGC 628. Semiregular star formation also occurs in nuclear starburst rings (e.g., Pastoriza 1975; Kennicutt et al. 1989; Elmegreen 1994; Crocker et al. 1996; Comerón et al. 2010; van der Laan et al. 2013; Väisänen et al. 2014), molecular cloud cores (Keto et al. 1991; Sánchez-Monge et al. 2014), debris from interacting galaxies (Wang et al. 2004; Bettoni et al. 2010; Tremblay et al. 2014), and galaxies along Mpc-scale cosmic filaments (Tempel et al. 2004).

Theory suggests that regular fragmentation in filaments is an indication of gravitational instabilities operating at the fastest growing wavelength (e.g., Inutsuka & Miyama 1992; see Section 3 below). Spiral arms filaments presumably differ from local globular filaments (Schneider & Elmegreen 1979). Spiral arms are often modeled as moving through gas over long distances, collecting it into thin dust lanes in what may be a quasi steady-state (Roberts 1969). Other models suggest that the filaments are transient (Dobbs & Bonnell 2008; Dobbs & Pringle 2013), building up until they reach a point of instability, such as a critical line density, and then collapsing into stars or dispersing by nonlinear effects (Chakrabarti et al. 2003).

The earliest theoretical models for gravitational collapse of gas in spiral arms estimated the growth rates and flow-through times and compared the resulting length and mass scales to the available cloud observations (Elmegreen 1979; Cowie 1981; Tomisaka 1987). Early simulations showed the buildup of a magnetogravitational instability in spiral arms (Kim & Ostriker 2001, 2002) and the important role of gaseous self-gravity in forming giant molecular clouds (Kim & Ostriker 2007). Modern simulations
show detailed cloud structure, including regularly spaced clumps in spiral arms with adaptive mesh gravitational hydrodynamics (Renaud et al. 2013), and highly resolved cloud substructures using particle hydrodynamics with phase transitions (Bonnell et al. 2013), molecule formation (Dobbs et al. 2008; Duarte-Cabral & Dobbs 2016), and star formation feedback (Dobbs et al. 2011). Simulations also produce filamentary clouds, although in Benincasa et al. (2013) they were irregular with typically one clump per filament, and in Dobbs (2015) and Duarte-Cabral & Dobbs (2016) they were concentrated in the interarm regions as a result of sheared spiral arm clouds. The observations in the present paper show both arm and interarm filaments and in most cases they contain many clumps with a regularity in their spacing and brightness that is not typically present in simulations (except, e.g., Renaud et al. 2014).

Observations are still unclear about whether spiral arms trigger a net excess of star formation in a galaxy or merely concentrate the gas in the arms, providing the pearls-on-a-necklace appearance without changing the efficiency of star formation per unit gas (Elmegreen & Elmegreen 1986). There is abundant evidence that molecular clouds and star-forming regions are larger in the arms (e.g., Roberts & Stewart 1987; Colombo et al. 2014), but simulations that reproduce this effect do not necessarily have an excess of star formation (Dobbs et al. 2011, 2015), and the large regions that form can be unbound and easily dispersed in the interarms (Dobbs 2008). Observations by Koda et al. (2009) support this picture of loose cloud agglomeration and interarm dispersal. A simulation by Baba et al. (2017) also showed that molecular clouds go through the arms with little effect on their internal properties and star formation. Dobbs & Pringle (2009) modeled cloud flow in a spiral arm and reproduced well the Kennicutt–Schmidt relation between the surface densities of star formation and gas, but they also got no enhancement in the specific star formation rate in the arms.

Some observations show that molecular clouds are more self-gravitating in the arms (Hirota et al. 2011), and others show they are not (Donovan Meyer et al. 2013). Shabani et al. (2018) studied spiral arm triggering in a more conventional way, looking for age gradients of star clusters across the arms (Yuan & Grosbol 1981). They found cluster age gradients in the symmetric two-arm spiral galaxy NGC 1566, but not in M51 or NGC 628, and suggested that M51 has a transient tidal arm rather than a steady wave and NGC 628 is too weak to show a gradient. Another type of transient spiral was modeled by Baba et al. (2013). Transient spirals are not expected to have age gradients because they can accrete gas from both sides (Dobbs & Pringle 2010). A stellar age gradient was found in part of a spiral arm in M99 (Gonzalez & Graham 1996).

A related observation is of spiral arm spurs or feathers, which can be regular too (Sandage 1961; Lynds 1970; Elmegreen 1980; La Vigne et al. 2006; Puerari et al. 2014). Spurs can arise when the spiral arm condensations driven by self-gravity emerge into the interarms and twist around in a locally reversed shear flow (Balbus 1988; Kim & Ostriker 2002, 2006; Shetty & Ostriker 2006). Shear and other instabilities may contribute too, even without self-gravity (Wada & Koda 2004; Dobbs & Bonnell 2006; Kim et al. 2014, 2015; Sormani et al. 2017). A comprehensive analysis of spur formation with gravity and magnetic fields in a stationary two-arm spiral was made by Lee & Shu (2012) and Lee (2014). Renaud et al. (2014) suggested that the regularly spaced condensations inside spiral arms are from gravitational instabilities, and the spurs that trail the arms are from Kelvin–Helmholtz-type instabilities.

To investigate the role of gravitational collapse in galactic-scale filaments, we examined for this paper Spitzer Space Telescope Infrared Array Camera (IRAC) images of nearby spiral galaxies from the Spitzer image archive (e.g., NGC 300, M74, M63, M83, M100, M101, NGC 6946, and IC 342). All of these galaxies were found to contain bright infrared (IR) condensations, or “clumps,” somewhat regularly spaced along thin dust filaments that sometimes extend for several kpc. Because these structures could be a key to understanding how spiral waves trigger star formation, we chose one example, M100, and measured the clump properties from the archival images. Clumps in the nuclear ring of M100 were studied previously by Knapp et al. (1995). The clumps in the spiral arms observed here are found to have little correspondence with optical features, suggesting embedded or highly obscured star formation if they are powered internally. This latter result needs further study, perhaps with higher resolution IR observations, because Prescott et al. (2007) and Schinnerer et al. (2013) found relatively little embedded star formation in the galaxies they observed. Our previous observations (Elmegreen et al. 2014) found a few regions that were visible in the IRAC bands and invisible in the SDSS images.

The first IRAC observations showing clumpy spiral arm structure were for M81 in Willner et al. (2004). Calzetti et al. (2005) studied clumps in the main spiral arms of M51, combining 8 μm with 24 μm and other observations in ~500 pc apertures to determine the star formation rates. Foyle et al. (2013) also observed regularly spaced spiral arm clumps at IRAC 8 μm and with Spitzer and Herschel FIR in M83; they found $10^7$–$10^8 M_\odot$ gas masses on scales of 200–300 pc with heating mostly by internal star formation. The structures reported in the present paper are similar to these morphologically, but generally smaller and more pervasive, with diameters of ~130 pc and spacings of ~410 pc.

**2. Observations**

**2.1. Morphology**

Figure 1 shows an IRAC image of M100 from the Spitzer website.$^4$ The image is a composite of 3.6, 4.5, 5.8, and 8 μm images. The galaxy is composed of numerous clumpy filaments in dust emission, which make it different from the usual view in optical images. The right-hand side of Figure 1 shows the Very Large Telescope (VLT) Focal Reducer and Low-dispersion Spectrograph (FORS) image of M100 in optical bands $R$, $V$, and $B$ to the same scale.$^5$ The thin filaments and semiregular spacings of clumps in the IRAC image are barely perceptible in the optical. Some IR filaments are dust lanes in optical light without any evidence for the clumps, some are haphazard strings of HII regions or bright irregular star complexes, and some are completely indistinct.

To highlight this difference, Figure 2 shows enlargements of select regions from the Spitzer and VLT images, displayed on the same scale. Most of the IR clumps are regularly spaced and similar to each other along the filaments, but the optical features are irregular in both extinction and emission from Hα and young stars.

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$^4$ Credit: NASA/JPL-Caltech: http://www.spitzer.caltech.edu/images/5208-sig12-007-The-Swirling-Arms-of-the-M100-Galaxy.

$^5$ Credit: ESO; http://eso.org/public/images/potw1330a/.
Figure 3 shows the ratio of the 8 $\mu$m to the Spitzer MIPS 24 $\mu$m emission. This ratio has the effect of removing the local background to highlight small-scale near-infrared (NIR) features, like an unsharp-mask image. It occurs because the MIPS image has an angular resolution of 7′′1, the 8 $\mu$m image has a resolution of 2′′4 (Chambers et al. 2009), and most of the 8 $\mu$m features have 24 $\mu$m counterparts. The ratioed image brings out the clumps well, showing them as white dots aligned along nearly all of the larger-scale structures.

2.2. Measurements of Clump Properties

The Spitzer image of M100 was examined for small bright clumps with central peaks and red colors. Several small white clumps were avoided as they were thought to be young regions that have partially broken through the dust. Stars are very blue in these images and were easily avoided.

The position and flux of each clump were first measured in four IRAC bands using the Image Reduction Analysis Facility (IRAF) task phot with a measurement aperture of 2 pixels radius and background subtraction from an annulus between 3 and 4 pixels away from the center. This background region was chosen because the clumps tend to be separated by 7 pixels (see below), and then the background lies between the clumps. The zero points for conversion of counts to magnitudes were taken from the IRAC instrument handbook. The positions and magnitudes for the clumps in the filaments are given in Table 1.

Another set of measurements was made for the clumps on the filaments. Here, the clump fluxes were determined with phot in a 1.5 pixel radius aperture with no background annulus, and a background for subtraction was determined from other phot 1.5 pixel apertures located midway between each pair of clumps. Thus, for this second set, the background for subtraction was taken to be the average of the fluxes from the two filament midpoints on either side of the clump; for clumps at the ends of the filaments, the background was taken to be the flux from the one adjacent filament midpoint. This second measurement using filament midpoints as backgrounds was designed to get the brightnesses of the clumps relative to the adjacent filaments, and also the color excesses of the clumps relative to the colors of the adjacent filaments. The clump magnitudes determined in this second way are listed in Table 2, including only those with measurable interclump fluxes.

Clumps were selected for measurement based on their compactness and brightness. For the first method discussed above, they are complete down to $\sim$13.5 mag at 8 $\mu$m, $\sim$15.5 mag at 5.6 $\mu$m, $\sim$18 mag at 4.5 $\mu$m, and $\sim$18 mag at 3.6 $\mu$m. We determined these limits by blocking each chosen clump with a black dot on Figure 3 as we measured it, using the clump position to the nearest half pixel, and then measuring fainter and fainter clumps until it was clear that there were no remaining small clumps brighter than the limits. This does not count multiple or highly elliptical clumps or elongated bright regions that have larger total brightnesses, as we are interested only in compact clumps like those that dot the filaments. We also ran SExtractor to search for clumps on several types of images, including Figures 1 and 3, but the background varies too much from clump to clump to get any reasonable match to what we could find by eye.

In the end, we selected 422 clumps as representative of the whole galaxy. Of these, 147 are in 27 filaments, most of which have a spiral-like appearance or are in the main stellar density wave arms. Figure 4 identifies the 147 filament clumps using different symbols and colors for each filament. The 275 nonfilament clumps are shown as black dots. There are many more clumps that are diffuse or faint that are ignored.

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5. http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/instrumenthandbook/
2.3. Separation Distribution

Figure 5 plots on the left the distribution function of the separation between adjacent clumps on each filament with three or more clumps. The units are in pixels on the Spitzer FITS images, which are 0"75 in size. A pixel corresponds to 59 pc at a distance of 16.2 Mpc from NED. The peak in the distribution at 7 pixels corresponds to 410 pc. This separation distribution does not consider the inclination of the galaxy, which is 30° (Knapen et al. 2002); deprojection would increase the separations by at most 13% along the major axes, which is not significant.

The right-hand side of Figure 5 shows as a histogram the relative difference in the separations between three adjacent clumps, calculated as $2(S_{i-1} - S_{i+1,i})/(S_{i-1} + S_{i+1,i})$ for adjacent clump indices $i - 1$, $i$ and $i + 1$ along a filament and separation $S$. The relative difference in separation is small and it shows two peaks, one within 0.2 of 0 and another around 0.66. The first peak corresponds to equal separations between clumps, i.e., a regularity in their position along the filament. The second peak corresponds to a gap in a regular spacing. That is, for a gap in the midst of a regular spacing of 1 unit, the distance between the first two clumps that straddle the gap is 2 units, and the distance between the next two clumps in the sequence is 1 unit. Thus the relative difference is $2 \times (2 - 1)/(2 + 1) = 0.66$. According to the right-hand side of Figure 5, 48 relative separations out of the total of 93 (52%) in the plot are regular or regular with a gap where there is one missing. This confirms the appearance by eye of the regularity of the clumpy filaments in Figures 1–3.

Also on the right of Figure 5, there are circles and horizontal error bars representing the mean and variance, which show the number of clumps on each filament (y-axis) versus the relative separations along these filaments (x-axis). Only filaments with more than three clumps are considered. The points show a more precise regularity, i.e., a smaller number on the x-axis, for filaments that contain fewer clumps. Longer filaments with many clumps have a slightly more irregular spacing between the clumps. For clarity in plotting, the vertical dimension is offset from the integer number of clumps in the filament by a small random amount.

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Figure 2. Cutouts from Figure 1 showing clumpy filaments from the Spitzer IR image on the left and the same regions from the VLT optical image on the right. The regularity of the star-forming clumps is clear in the IR images, yet there is often little trace of it in the optical.
The numerous white dots that line up on most of the spiral-like filaments and spurs show the IR clumps studied here. MIPS 24 \( \mu m \) emission also comes from these clumps, but the angular resolution at 24 \( \mu m \) is several times larger than the clump size, so the MIPS image provides a good model to divide out the large-scale structure and highlight the 8 \( \mu m \) clumps. The dark regions around some concentrations of clumps are from the division by broad 24 \( \mu m \) emission.

### Table 1
Clumps in Filaments with Background Annulus Subtracted

| R.A.          | Decl.       | [3.6]  | [4.5]  | [5.8]  | [8.0]  |
|---------------|-------------|--------|--------|--------|--------|
|               |             | mag    | mag    | mag    | mag    |
| Filament 1,   | blue \( \alpha \) |        |        |        |        |
| 12:22:46.4110 | 15:48:37.915 | 17.86 ± 0.89 | 17.71 ± 1.03 | 15.48 ± 0.47 | 13.52 ± 0.26 |
| 12:22:46.4110 | 15:48:34.165 | 17.41 ± 0.72 | 17.18 ± 0.81 | 14.93 ± 0.36 | 13.16 ± 0.22 |
| 12:22:46.3851 | 15:48:28.540 | 17.58 ± 0.79 | 17.45 ± 0.92 | 15.35 ± 0.45 | 13.66 ± 0.31 |
| 12:22:46.4371 | 15:48:25.915 | 16.84 ± 0.57 | 16.43 ± 0.58 | 14.81 ± 0.36 | 13.08 ± 0.25 |

(This table is available in its entirety in machine-readable form.)

### Table 2
Clumps in Filaments with Interclump Subtracted

| R.A.          | Decl.       | [3.6]  | [4.5]  | [5.8]  | [8.0]  |
|---------------|-------------|--------|--------|--------|--------|
|               |             | mag    | mag    | mag    | mag    |
| Filament 1,   | blue \( \alpha \) |        |        |        |        |
| 12:22:46.4110 | 15:48:34.165 | 18.64 ± 0.85 | 18.28 ± 1.01 | 15.95 ± 0.49 | 14.19 ± 0.30 |
| 12:22:46.3851 | 15:48:28.540 | 19.70 ± 0.86 | 19.68 ± 1.04 | 17.71 ± 0.53 | 15.80 ± 0.33 |
| 12:22:46.4371 | 15:48:25.915 | 18.97 ± 0.74 | 18.25 ± 0.83 | 16.69 ± 0.44 | 15.08 ± 0.28 |

(This table is available in its entirety in machine-readable form.)
Figure 4. *Spitzer* image of M100 as in Figure 1 with 422 bright clumps indicated, including 147 with various symbols and colors assigned to 27 distinct filaments, as listed in Tables 1 and 2.

Figure 5. (left) Histogram showing the distribution of 120 separations between clumps on the 27 filaments indicated in Figure 4. The separations are measured in pixels on the *Spitzer* image, which are 0.75″ and correspond to 60 pc. The peak occurs at 410 pc. (right) Histogram of the relative separations between clumps on the filaments with three or more clumps. The relative separation is the difference between two adjacent separations divided by their average separation. The histogram peaks between 0 and 0.2 relative separations, which corresponds to equally spaced clumps, and again between 0.6 and 0.8, which corresponds to a gap between nearby equally spaced clumps. The circles and horizontal lines are the means and variances of the relative separations for the individual filaments with more than three clumps. The circle at (0.89, 2) corresponds to filament 17 with red squares in Figure 4; it has four clumps with the inner two close together and the outer two separated by almost the same distance from their adjacent inner clumps, giving a very small variance in the separation differences for each set of three contiguous clumps.
2.4. Magnitude Distribution

Figure 6 shows, in blue, the apparent magnitude distribution function at 8 μm for all 422 clumps. This distribution is complete in the bright part beyond the peak (see above). Figure 6 also shows, in red, the magnitude distribution for clumps in all of the identified filaments, and in black, the clumps in the main spiral arm, which is to the west and south of the center (the corresponding symbols in Figure 4 are magenta squares, cyan squares, and green crosses). The main spiral arm has brighter clumps than elsewhere, as evident also from the optical image. The luminosity scale at the top of this figure is from the conversion of flux density into luminosity, assuming a width for the IRAC4 filter equal to 2.88 μm, from the half-power points given in the IRAC instrument handbook. The distance modulus is 31.05.

The right-hand part of Figure 6 plots as a histogram the differences in 8 μm magnitudes between adjacent clumps. The circles and horizontal lines are the means and variances of the magnitude differences for each filament with more than two clumps (as opposed to more than three clumps for the separation differences). The dispersion in the histogram for the differences is 0.46 mag, and the dispersion in the magnitudes themselves, from the left-hand panel, is 1.01 mag. The expected dispersion of a random sample of differences drawn from a Gaussian distribution like the magnitude distribution on the left is $\sqrt{2}$ times the dispersion of the Gaussian, which would be 1.42 mag in our case. The dispersion of the observed differences is only 0.32 times the expected dispersion of the differences if the adjacent clumps were drawn from a random sample. Thus the adjacent clumps are closer to each other in 8 μm brightness than they would be in a random distribution, by a factor of 3.1. We get approximately the same result considering only clumps brighter than 13.5 mag at 8 μm for the total magnitude dispersion (0.76 mag in that case) and considering only adjacent clumps where both are brighter than 13.5 mag at 8 μm (0.42 mag dispersion for the mag differences), giving the ratio 2.5. These results, combined with the regularity shown in Figure 5, suggest that clump formation in galactic-scale filaments is a coherent process.

2.5. Color Distribution

Figure 7 shows color–magnitude and color–color diagrams of the clumps, where the colors and magnitudes were determined in the two ways mentioned above, once with background subtraction from an annulus that lies between the clumps on average (top panels), and again with the filament brightness used for the background subtraction (middle panels). The similarity of the 3.6 and 4.5 μm fluxes ([3.6]–[4.5] is small) and the red colors at 5.8 μm and 8 μm indicate the presence of stars at the shorter wavelengths and warm dust and PAH emission at the longer wavelengths.

In the top panels the [3.6]–[4.5] color averages 0.20 ± 0.03 mag with dispersion $\sigma = 0.33$ mag, the [4.5]–[5.8] color averages 2.17 ± 0.03 mag with $\sigma = 0.40$ mag, and the [5.8]–[8.0] color averages 1.75 ± 0.02 mag with $\sigma = 0.19$ mag. In the middle panels, the [3.6]–[4.5] color averages 0.31 ± 0.02 mag with $\sigma = 0.27$ mag, the [4.5]–[5.6] color averages 2.04 ± 0.05 mag with $\sigma = 0.50$ mag, and the [5.8]–[8.0] color averages 1.71 ± 0.02 mag with $\sigma = 0.21$ mag.

These colors compare well with models of emission from star-forming regions. Dale et al. (2001) show model galaxy spectra with a jump equal to factor of ~5 from 4.5 μm to 5.8 μm in their Figure 5, and that factor corresponds to a color...
Gutermuth et al. (2009) consider PAH colors as a source of contamination for studies of protostars in star-forming regions; their Figure 15 shows the PAH region in color–color space where $[4.5]-[5.8] \sim 1-2$ and $[3.6]-[4.5] \sim 0-1$, as for our colors. Protostar envelopes are redder in $[3.6]-[4.5]$ than our clumps because of their hotter dust, and protostar disks are bluer in $[5.8]-[8.0]$ (Allen et al. 2004). The IRAC colors of the diffuse interstellar medium in the Milky Way are also close to our $[4.5]-[5.8]$ colors. Flagey et al. (2006) measure these colors outside regions of star formation and tabulate the ratios in their Table 1. Typically the ratio of $4.5 \mu m$ to $5.8 \mu m$ emission is $\sim 1/8$, which corresponds to a color of $\sim 2.3$, similar to that in Figure 7. The ratio of $5.8 \mu m$ to $8.0 \mu m$ in Flagey et al. (2006) is smaller, $\sim 0.3$, which corresponds to a color of 1.2 mag, whereas we measure $[5.8]-[8.0] \sim 1.5-2$ in the top panels of Figure 7. This difference implies that the $8 \mu m$ emission is relatively larger in the M100 clumps than in local diffuse clouds. Without longer wavelength observations at comparable resolution (the clumps are a few arcseconds in size), we cannot

**Figure 7.** Color–magnitude and color–color diagrams of the clumps in the filaments of M100, using the same symbols as in Figure 4 to indicate specific filaments. The units on both axes are magnitudes. The top row calculates magnitudes and colors using circular apertures of 2 pixels radius and background subtraction using an annulus from 3 to 4 pixels away from the clump center. The middle row determines the flux from each clump using a circular aperture of 1.5 pixel radius and subtracts a background flux from the underlying filament, taken to be the average of the fluxes in 1.5 pixel radius apertures on each side of the clump, midway to the next clump. The magnitudes and colors of the clumps are calculated from these filament-subtracted fluxes. The bottom row uses the same clump and average-filament fluxes as the middle row, but the colors plotted are the excess colors of the clump compared to the average underlying filament.
make a more complete spectral energy distribution (SED) and determine the contributions from stars and dust, nor can we get the dust temperature and total dust luminosity.

The bottom panels in Figure 7 show the excess colors of the clumps compared to the filaments. There is a lot of scatter, but the clumps are slightly redder in [3.6]–[4.5], by 0.044 ± 0.005 mag, than the adjacent filaments (with σ = 0.06), about the same in [4.5]–[5.8] with an excess of only 0.042 ± 0.010 mag (σ = 0.12), and slightly bluer in [5.8]–[8.0], with an excess of −0.011 ± 0.004 mag (σ = 0.05). These excesses suggest that the filaments show a little more underlying disk starlight than the clumps.

2.6. Equivalent Stellar Masses

The equivalent stellar masses that excite the clumps can be determined from the IRAC fluxes and the bolometric magnitude of a young stellar population. These stellar masses do not necessarily correspond to embedded stars because some of the heating can come from adjacent stars that are visible optically. Nevertheless, they provide a measure of the associated young stellar mass for each clump.

We first estimate the total IR luminosity for the clumps using the complete SEDs of galaxies tabulated by Xu et al. (2001). This tabulation gives flux density versus wavelength for six normal galaxies with 24 μm luminosities in the range from 10^{9} L_\odot to 10^{10.6} L_\odot, and for two starburst galaxies with 24 μm luminosities equal to 10^{9} L_\odot and 10^{11} L_\odot. The SEDs from Xu et al. (2001) were integrated over the total width of the four IRAC bands, which is from 3.18 to 9.33 μm (the lower half-power point for the 3.6 μm band and the upper half-power point for the 8 μm band, according to the IRAC instrument handbook), and they were also integrated over the full SED to give the total IR flux. The ratio of the total to the IRAC fluxes ranged from 22 for the lowest-mass normal galaxy to 12 for the highest-mass normal galaxy, and it was equal to 9.6 and 7.1 for the two starburst galaxies, respectively. The high values for low-mass normal galaxies reflect the dominance of background radiation on the dust heating as there is little star formation in these systems. The values decrease with increasing prominence of star formation because the PAH emission and hot dust emission in the IRAC bands goes up relative to the cool dust emission at longer wavelengths. We consider our clump SEDs to be most like the starburst SEDs because they enclose or are adjacent to regions of active star formation, as indicated by the juxtaposition of the clumps to H II regions and OB associations in Figure 2. Thus we take a ratio of ∼8 to convert the summed flux in all four IRAC bands to the total IR luminosity.

This ratio is consistent with the ratios of total IR luminosity to 24 μm, which is about 10, and 8 μm to 24 μm luminosity, which is about unity, for M51 where longer wavelengths were measured (Calzetti et al. 2005). It is similar also to that in Dale et al. (2005), who observe an approximately flat normalized flux density distribution, νfν versus the logarithm of the wavelength for galaxies in the Spitzer Nearby Galaxy Survey, considering that the ratio of the log-wavelength interval for the whole spectrum to the log-wavelength interval for IRAC is about 5 (that would make the total IR flux ∼5 times the summed IRAC flux).

To convert the total IR luminosity to the mass of associated young stars, we use the bolometric magnitude of a young stellar population given in Bruzual & Charlot (2003). This is −2.7944 for solar metallicity at less than 1 Myr age and −1.0321 at 10 Myr. Using 4.74 mag as the bolometric magnitude of the Sun, the bolometric luminosity per solar mass of young stars is

3. Origin of the IR Clumps

The equal spacings and similar magnitudes of the clumps on the filaments suggest that the condensations formed by a regular process such as a gravitational instability along the filament lengths. The separation should be the length of the fastest growing unstable mode. The appearance of multiple clumps on filaments, sometimes with a half dozen or more clumps, also implies that all parts of the filament formed at about the same time. Then all of the clumps collapsed together before the filaments could be dispersed by shear and star formation feedback.

Filament instabilities without a magnetic field were studied early on by Ostriker (1964) and Inutsuka & Miyama (1992), and with a magnetic field by Chandrasekhar & Fermi (1953), Stodolkievicz (1963), Nagaawa (1987), Nakamura et al. (1993), Tomisaka (1995), Fiege & Pudritz (2000), and others. When the filament has the equilibrium mass per unit length, μ = 2σ²/G for velocity dispersion σ, these authors found a dominant wavelength, or separation between condensations,
that is about 3.9 times the effective filament diameter, $D_{\text{eff}}$, which is $D_{\text{eff}} = 2\mu(\pi \rho)_{c}^{-1/2}$ for central density $\rho_c$. The growth rate for this mode is $\omega = 0.34 \times (4\pi G \rho_c)^{1/2}$. A filament confined by high pressure has a longer dominate wavelength and a slower growth rate because the mass per unit length is less at the same central density. A magnetic filament with an aligned field has about the same dominant wavelength if it is not highly confined by pressure because the instability occurs in a direction where the field exerts little force. If it is confined by pressure, then the field slows the growth as the wavelength increases.

Figure 2 shows good agreement with these expectations for the self-gravitational collapse of filaments. The separations appear to be 3–5 times the filament diameters, as expected for near-critical line densities. Figure 9 shows this more quantitatively. It plots a histogram of the ratio of the separation between adjacent clumps to the average clump diameter. The diameters were determined from the number of pixels in rectangles surrounding the clumps using the IRAF routine instat. We consider that the rectangles typically go to about 0.1 times the peak brightness and we assume the diameters go to 0.5 times the peak brightness. In this case the diameters used for Figure 9 are about 1.1 times the square roots of the ratios of the areas to $\pi$, measured in pixels like the separations. Figure 9 has a clear peak in the ratio of separation to diameter that is centered at around 3, and a tail toward a value of ~6, which could be from adjacent clumps with a gap between them (see Figure 4). This is the ratio expected if the clumps formed by gravitational instabilities.

The average gas densities inside the filaments are low because their apparent sizes are large. For example, if the gas mass is $\sim 100$ times the average stellar mass in Figure 8, which would be $\sim 3 \times 10^4 M_\odot$, corresponding to a low star-formation efficiency, and their diameters are typically $\sim 130$ pc as measured from the surrounding box sizes discussed above, then the average gas density is $\sim 2.1$ atoms cm$^{-3}$. Taking this density to be $\rho_c$ in the above equation, the corresponding collapse time is $t_{\text{coll}} = 2.9 (4\pi G \rho_c)^{-1/2} \sim 46$ Myr. This density is too low and the resulting time is too long to have a simultaneous collapse of many clumps along each filament. The filaments probably last only 10 Myr up to a few times 10 Myr, considering the distortions and shear of spiral arms. Thus the average gas density inside the filaments is probably much higher than what we see at the resolution of IRAC.

Dense filaments like the infrared dark clouds in the Milky Way (IRDC; e.g., Rathborne et al. 2007; Peretto & Fuller 2009) could be at the cores of our IRAC filaments. IRDC are opaque clouds observed against the bright background of diffuse IR emission from the Galactic plane. There is a 160 to 430 pc long IRDC in the Scutum–Centaurus arm (Goodman et al. 2014) that is a good candidate for a galactic-scale filament like the longer ones observed here. Jackson et al. (2010) also suggested that a self-gravitational instability made regular condensations in the Milky Way filament named “Nessie,” although that is on a much smaller scale with a 4.5 pc clump separation and a total length of 80 pc.

The kiloparsec lengths of many IRAC filaments imply that dynamical processes sweep up interstellar gas on this scale. For the main spiral arms, this process is presumably the usual density wave shock, which can have a length of several kpc for most of the regions inside corotation and possibly outside corotation too. The main spiral arms in M100 are of this type, as evident from the similar positions of broad stellar arms seen at 2 $\mu$m wavelength by the 2MASS survey (Skrutskie et al. 2006). Other filaments could be from shear inside the stellar arms, making spurs (Section 1). Figures 1 and 2 show more remote filaments too, with no apparent connection to the stellar arms seen in the 2MASS image. These remote filaments suggest there are large-scale gas motions independent of the main stellar spirals, possible from local instabilities or stellar feedback.

If the evolution timescale for the filaments is $\sim 10$ Myr, based on the expectation of shear rates and spiral wave motions, and the total mass of the measured clumps in the filament is $4.5 \times 10^5 M_\odot$ for this age, from above, then the ratio of the mass to the age is 0.45 $M_\odot$ yr$^{-1}$, which is lower than the total star formation rate in M100, $\sim 2.6 M_\odot$ yr$^{-1}$ (Kennicutt et al. 2011). For a 1 Myr timescale, the rate would be 0.89 $M_\odot$ yr$^{-1}$, which is still small. These small rates suggest that filament clumps are not the only drivers of star formation in M100. This conclusion is consistent with the other evidence given in the Introduction that spiral waves affect the total star formation rate by only small amounts. It is also consistent with the appearance of many other star-forming regions outside of the filaments. Still, the appearance of highly regular clump structures in numerous long filaments suggests that spiral arms trigger gas collapse and at least some cloud formation by gravitational instabilities.

4. Conclusions

Dust filaments in M100 revealed by Spitzer IRAC images tend to have a regular spacing of similar-mass clumps along their lengths, suggestive of a formation process involving gravitational instabilities in gas that was accumulated by the relative motion of spiral density waves and the associated

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8 https://www.ipac.caltech.edu/2mass/gallery/m100atlas.jpg
large-scale flows. The clump separation is typically 410 pc and the ratio of the separation to the clump diameter ranges from 2 to 4. Many filaments extend for several kpc. These regions appear to be galactic-scale analogs of local star-forming filaments and filamentary IRDCs, and they probably form and evolve in a similar way, making stars at the gravitating condensations. IRAC colors reflect their likely emission from PAHs and hot dust, as modeled for galactic star-forming regions. The effective stellar masses of the selected condensations average $3 \times 10^5 M_\odot$ for an age of 1 Myr, with a total effective mass in the range of $0.9-4.5 \times 10^5 M_\odot$ for the measured clumps in the filaments if we assume ages of 1 and 10 Myr, respectively. The ratio of these filament clump masses to the assumed ages falls short of the star formation rate in M100 by factors of 3–6, which is consistent with the relatively small influence that spiral arms generally have on total star formation rates. The importance of the observation lies in the identification of one process by which spiral waves interact dynamically with the interstellar medium to form new clouds.

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