Gas Engaged in Noncircular Motions in LITTLE THINGS Dwarf Irregular Galaxies

Deidre A. Hunter1,2, Lauren Laufman1,2,5, Se-Heon Oh3, Stephen E. Levine1, and Caroline E. Simpson4

1Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA
2Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ 86011, USA
3Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul, Republic of Korea
4Department of Physics, Florida International University, CP 204, 11200 SW 8th Street, Miami, FL 33199, USA

Received 2019 March 12; revised 2019 May 14; accepted 2019 May 15; published 2019 June 18

Abstract

We have examined gas engaged in noncircular motions in 22 of the nearby LITTLE THINGS dwarf irregular galaxies. The H I data cubes have been deconvolved into kinematic components—bulk rotation and noncircular motions—to produce maps of integrated gas, velocity field, and velocity dispersion in the different components. We found significant regions of gas engaged in noncircular motions in half of the galaxies, involving 1%–20% of the total H I mass of the galaxy. In one galaxy we found a pattern in the velocity field that is characteristic of streaming motions around the stellar bar potential and star formation at the end of bar. Two galaxies have large-scale filamentary structures found in their outer disks, and these filaments could be transient instabilities in the gas. We found no spatial correlation between noncircular motion gas and enhanced star formation. We found noncircular motion gas in only one galaxy associated with higher H I velocity dispersion.

Key words: galaxies: irregular – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: star formation

1. Introduction

Most dwarf irregular galaxies (dIrrs) are engaged in ongoing star formation at gas surface densities that are so low that, according to models, dIrrs should not be able to form star-forming clouds (Hunter et al. 1998; Bigiel et al. 2010; Barnes et al. 2012; Elmegreen & Hunter 2015). Thus, dIrrs are an extreme environment in which physical models for star formation and galaxy growth can be observed and tested.

In some dIrrs gas is observed to be engaged in noncircular motions, and model dwarfs formed in cosmological simulations also exhibit gas in noncircular motions due, for example, to strong azimuthal bisymmetric fluctuations (Read et al. 2016; Oman et al. 2019). Collisions between noncircularly moving gas and gas engaged in bulk rotation could provide one mechanism for bringing gas together into clouds that are dense enough to be self-gravitating. Star formation that is associated with noncircular motions in the atomic hydrogen H I could be triggered internally by, for example, flows around stellar potentials or stellar winds and explosions or triggered externally by interactions with another galaxy, ram pressure disturbances, or extragalactic accretion. Here we examine the nature of noncircular motions of H I and the role they play in the evolution of nearby dIrrs.

2. Data

We used the LITTLE THINGS (Local Irregulars That Trace Luminosity Extremes, The H I Nearby Galaxy Survey; Hunter et al. 2012) sample of dIrr galaxies. LITTLE THINGS is a multibandwidth survey of 37 dIrr galaxies and 4 blue compact dwarfs (BCDs) aimed at understanding what drives star formation in tiny systems. The LITTLE THINGS galaxies were chosen to be nearby (<10.3 Mpc), contain gas so they could be forming stars, and cover a large range in dwarf galactic properties, such as the rate of star formation. The LITTLE THINGS data sets include H I spectral line maps obtained with the National Science Foundation’s Karl G. Jansky Very Large Array (VLA). The H I data cubes combine observations in the B, C, and D arrays and are characterized by high sensitivity (~1 mJy beam−1 per channel), high spectral resolution (1.3 or 2.6 km s−1), and moderately high angular resolution (frequently, ~6′). Note that the pixel scale is 1.5′.

We also have ancillary multibandwidth data including UBV, Hα, and GALEX far-ultraviolet (FUV) images.

This study includes the 22 LITTLE THINGS galaxies whose H I rotation curves were analyzed by Oh et al. (2015). In an algorithm developed by Oh et al. (2008, 2015), we fit Gaussians to H I position–velocity data cubes at positions where multiple kinematic components were found. Oh et al. used the H I data cubes in which channel maps were made using robust weighting. This choice of weighting results in maps with a spatial resolution that is somewhat higher compared to that of naturally weighted maps and the beam shape has less extended wings. The kinematic components under consideration include ordered, circular rotation (bulk) and noncircular motion. They were deconvolved iteratively using the following steps: (1) estimate an initial rotation curve from ellipse fits to 3.6 μm images and single Gaussian fits to the intensity–velocity profiles along the major axis of the galaxy in the H I data cube, (2) create a model velocity field, (3) extract the bulk velocity field using multiple Gaussian decomposition, and (4) iterate using a full tilted-ring model to determine the rotation curve parameters. In this way, the true bulk rotation could be determined and noncircular motions isolated. Gas engaged in noncircular motions was classified as being strong noncircular (snonc) if the intensity peak is higher than that of the bulk motion gas at that position or weak noncircular (wnonc) if the intensity peak is lower than that of the bulk motion gas at that position. We refer the reader to

5 Current address: Department of Astronomy, University of Wisconsin-Madison, 475 N. Charter Street, Madison, WI 53706, USA.

6 The VLA is a facility of the National Radio Astronomy Observatory. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Oh et al. (2008, 2015) for a detailed description of the deconvolution process.

The final products of the deconvolution are separate maps of the bulk, snc0, and wnc0 gas components. Oh et al. (2015) made maps with signal-to-noise (S/N) cuts at 2 and at 3. We chose to use the maps with a cut at an S/N of 3. For each kinematic component, we have maps of the H1 integrated intensity (moment 0), velocity field (moment 1), and velocity dispersion (moment 2). The galaxies used in this study and their observational and physical properties that are useful are listed in Table 1.

As a check on the data, we summed, as an example, DDO 133’s bulk moment 0 and snc0 moment 1 maps (the wnc0 map was not available) and compared it to the total H1 moment 0 map. We found that the sum of the components reproduces the total H1 map both in terms of internal morphology and integrated intensity but with increased noise. In some of the galaxy bulk maps, the places where large snc0 regions occur appear as blank. This is due to the S/N cut that eliminates the low S/N bulk motion gas where it is dominated by the snc0. We can see that all kinematic components are, nevertheless, present in those regions from intensity–velocity plots at spots within the snc0 regions shown below in Section 3.2.

We examined the snc0 and wnc0 moment 0 maps for significant features. The noncircular motion gas maps have lots of noise, but we were looking for large, coherent regions of gas such as blobs or filaments. These kinematically coherent regions connect both spatially and in velocity space over at least 30 pixels which have an S/N greater than 3. A spatial pixel is 1.5′ and the channel width is either 2.58 km s⁻¹ or 1.29 km s⁻¹, as given in Table 1. So, for example, a region with a 6 pixel diameter would be 31 pc in diameter in IC 1613 or 450 pc in DDO 52, and a 30 pixel area would be 1.2 times the beam area for IC 1613 and 1.7 times the beam area of DDO 52.

The regions were identified on snc0 moment 0 (snc0) maps by eye as a contiguous region of pixels. The regions are plotted on the snc0, snc0 moment 1 (snc1), total H1 moment 0 (H1 mom0), total H1 moment 1 (H1 mom1), FUV, Hα, and V-band images of the galaxy. These figures are shown in Figures 1 through 11 for the 11 galaxies in which such features were found. Galaxies without significant noncircular motion gas features have a zero in the column for the number of regions, Nreg, in Table 1.

The regions were encircled with a circle, ellipse, or polygon, and we measured the statistics of the region within that geometrical shape. The properties of the regions are given in Table 2 and include the R.A. and decl. of the center; the major axis, minor axis, and position angle (P.A.) of the region, if not a polygon; the encircled area in square-arcseconds; the H1 mass; the surface density of the gas averaged over the region; and the...
For CVnIdwA, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as follows: moment 0 maps are Jy beam$^{-1}$ ms$^{-1}$; snonc1, total H I mom1, and total H I mom2 maps are km s$^{-1}$; the FUV image is in counts s$^{-1}$ that can be converted to erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ by multiplying by $1.4 \times 10^{-15}$; the Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by $3.975 \times 10^{-18}$ (Hunter & Elmegreen 2004); and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5 \log(counts/600) = V - 21.56 - 0.013 \times (B - V)$ (Hunter & Elmegreen 2006).
Table 2
Region Properties

| Galaxy   | Region   | R.A. (hh:mm:ss.s) | Decl. (dd:mm:ss) | \(l_{\text{maj}}\) (arcmin) | \(l_{\text{min}}\) (arcmin) | P.A. (deg) | Area (arcmin^2) | log Mass \((M_\odot)\) | log \(\Sigma_{\text{int}}\) \((M_\odot\text{pc}^{-2})\) | \(\Delta V\) (km s^-1) |
|----------|----------|-----------------|-----------------|-----------------|-----------------|---------|----------------|----------------|----------------|----------------|----------------|
| CVnIBa   |          |                 |                 |                 |                 |         |                 |                 |                 |                 |                 |
| DDO 47   |          | 12:38:38.0      | +32:45:50       | 23.2            | 12.0            | 0        | 576             | 6.384 ± 0.002  | 1.139 ± 0.002  | −2              |                 |
|          |          |                 |                 |                 |                 |         |                 |                 |                 |                 |                 |
| DDO 70   |          | 9:59:48.8       | +19:39:23       | 29.2            | 15.1            | 180      | 981             | 4.903 ± 0.003  | 0.311 ± 0.003  | 6               |                 |
| DDO 126  |          | 12:27:03.9      | +37:08:28       | 14.5            | 9.6             | 140      | 371             | 6.362 ± 0.005  | 1.040 ± 0.005  | 5               |                 |
| DDO 133  |          | 12:32:50.9      | +31:34:52       | 19.4            | 11.9            | 30       | 576             | 5.232 ± 0.007  | 0.014 ± 0.007  | −5              |                 |
| DDO 168  |          | 13:14:24.6      | +45:54:30       | 13.0            | 11.9            | 180      | 317             | 6.094 ± 0.005  | 0.955 ± 0.005  | −5              |                 |
|          |          |                 |                 |                 |                 |         |                 |                 |                 |                 |                 |
|          |          | 12:04:46.9      | −12:50:11       | 0.0             | 0.0             | 0        | 3992            | 5.371 ± 0.002  | 0.489 ± 0.002  | −3              |                 |
The regions in DDO 210 are particularly uncertain because of the limited rotation and the location of the features in the outer edges of the galaxy. The ability to measure the velocity of features and the velocity offset is limited by the fact that the features are extended and cover a range of velocities. The velocities of the wnonc regions are outlined with polygons and so the difference in velocity compared to the surrounding gas in bulk ordered rotation. The mass of the region is the mass measured in the wnonc0 map and the velocity is the median in the encircled area on the wnonc1 map.

### 3. Results

#### 3.1. Streaming Motions

##### 3.1.1. DDO 133

In optical images, DDO 133 appears to have a stellar bar. This is visible as a rotation in the position angle of isophotes between the inner and outer galaxy. In the V-band image shown in Figure 12 one can see the bright, boxy inner structure that is the stellar bar and the more diffuse oval structure that is the stellar disk. The bar is outlined on other images in Figure 13. Here we have included a velocity map of the weak noncircular gas map (wnonc1) where we have identified two wnonc regions that are coincident with the northern end of the bar (wnonc region 1) and the upper part of the body of the bar (wnonc region 2). Properties of the two wnonc regions and the bar are given in Table 3. The wnonc regions in DDO 133 are located on a ridge of H I in the mom0 map. Furthermore, there is a clump that is bright in Hα and FUV associated with wnonc region 1 at the end of the stellar bar.
Figure 2. For DDO 47, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total HI moment 0 (mom0), total HI moment 1 (mom1), total HI moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s⁻¹ cm⁻² by multiplying by 0.356 × 10⁻¹⁸ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using –2.5 log(counts/1200) = V – 21.83 – 0.045 × (B − V) (Hunter & Elmegreen 2006).
Figure 3. For DDO 50, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total HI moment 0 (mom0), total HI moment 1 (mom1), total HI moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s⁻¹ cm⁻² by multiplying by 0.667 × 10⁻¹⁸ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using −2.5 log(counts/1200) = V − 21.72 − 0.016 × (B − V) (Hunter & Elmegreen 2006).
Figure 4. For DDO 53, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by 0.479 $\times$ $10^{-18}$ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5\log$(counts/180) = V – 25.04 – 0.032 × ($B$ – $V$) (Hunter & Elmegreen 2006).
Figure 5. For DDO 70, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by $0.673 \times 10^{-18}$ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5 \log$(counts/1200) = $V - 21.73 + 0.017 \times (B - V)$ (Hunter & Elmegreen 2006).
Figure 6. For DDO 126, features identified on strong noncircular moment 0 (snonc0), strong noncircular moment 1 (snonc1), total HI moment 0 (mom0), total HI moment 1 (mom1), total HI moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by 0.678 $\times 10^{-18}$ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5 \log(\text{counts}/1200) = V - 21.63 - 0.017 \times (B - V)$ (Hunter & Elmegreen 2006).
Figure 7. For DDO 133, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s⁻¹ cm⁻² by multiplying by 0.419 × 10⁻¹⁸ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using −2.5 log(counts/1200) = V − 21.65 − 0.017 × (B − V) (Hunter & Elmegreen 2006).
For DDO 168, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by 0.435 × 10$^{-18}$ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5 \log(\text{counts}/1200) = V - 21.82 + 0.045 \times (B - V)$ (Hunter & Elmegreen 2006).
Figure 9. For DDO 210, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, H\(\alpha\), and V-band maps. There is no H\(\alpha\) emission in DDO 210. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The V-band image is in counts that can be converted to a Johnson V magnitude using 
\[ -2.5 \log(\text{counts}/200) = V - 25.05 + 0.022 \times (\beta - V) \] (Hunter & Elmegreen 2006).
Figure 10. For IC 1613, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by 0.272 $\times$ 10$^{-18}$ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5 \log$(counts/600) = $V - 20.76 + 0.007 \times (B - V)$ (Hunter & Elmegreen 2006).
Figure 11. For Haro 36, features identified on strong noncircular moment 0 (snonc0) maps shown on snonc0, strong noncircular moment 1 (snonc1), total H I moment 0 (mom0), total H I moment 1 (mom1), total H I moment 2 (mom2), FUV, Hα, and V-band maps. Properties of the regions are given in Table 2. The color bar units are as in Figure 1. The Hα image is in counts that can be converted to erg s$^{-1}$ cm$^{-2}$ by multiplying by 0.754 × 10$^{-18}$ (Hunter & Elmegreen 2004) and the V-band image is in counts that can be converted to a Johnson V magnitude using $-2.5 \log(\text{counts/900}) = V - 23.11 + 0.007 \times (B - V)$ (Hunter & Elmegreen 2006).
In the upper left panel of Figure 13, velocity contours (in rainbow colors) have been placed on the V-band image of DDO 133. Note that along the outside edges of the bar (outlined in black), there is a crinkle pattern in the velocity contours. The same crinkle pattern along the edges of the bar are also seen by Lin et al. (2013) in the velocity field of the spiral galaxy NGC 1097. Their hydrodynamical simulation reproduces the velocity field pattern through streaming motions of the gas along the bar. Furthermore, it seems likely that the star formation at the end of the stellar bar is a result of gas piling up at the ends from streaming motions around the bar, and that this is also the cause of the wnoe motions there. The buildup of gas at the end of the bar could also have been influenced by the formation of an H I hole, which might once have been an expanding bubble, to the east of the northern end of the bar. This hole is evident as the circular purple region at the northern end of the mom0 image in the bottom left panel of Figure 13.

3.1.2. DDO 47

DDO 47 also seems to have a crinkle pattern in the H I velocity contours as shown in the velocity field (mom1) image in Figure 14. However, unlike DDO 133 a stellar bar is not obvious. There is a small elongated structure (red in the V image in Figure 14) near the center of the galaxy, but it is associated with star formation in the FUV image in Figure 2 and it is not clear that it is a bar structure. According to Bosma (1981), kinematic patterns like that due to a bar can also be the result of warps in the H I disk.

Alternatively, in a study of the gas structure in DDO 47, Gentile et al. (2005) suggest that the filamentary structure seen in the total H I is a spiral structure. In fact, the integrated H I mom0 map (the middle panel of Figure 14) has the general appearance of a flocculent spiral structure. One can see that the crinkles seem to follow the density patterns of the arms (see Section 3.2). While dwarf galaxies do not rotate fast enough to sustain proper spiral arms (Gallagher & Hunter 1984), it is possible for arm-like modes of instabilities to form. However, in dwarfs these instabilities would be transient and likely of a shorter timescale than the rotational period of the galaxy; thus they would break up swiftly and appear more messy than traditional arms (Levine & Sparke 1994). We could be seeing DDO 47 in the midst of one of these transient states.

Another consideration is that these instability modes can be dramatically influenced by the dark matter distribution in the galaxy. The total mass to stellar mass ratio in the central region of a galaxy compared to that in the disk influences what instability modes can be supported or if the modes will be damped and dispersed (Boldrini et al. 2019). We do not have the total mass to stellar mass ratio in the central region, but we do have the ratio of the dynamical mass to the baryonic mass from Oh et al. (2015). We use H I plus stars instead of stellar mass alone because the baryonic mass of dIrrs is dominated by the gas. We plot the fraction of gas engaged in snone features against the ratio of the dynamical mass to the baryonic mass $M_{\text{dyn}}/M_{\text{bary}}$ in Figure 15. DDO 47 is plotted as a red X and is shown as an upper limit in $M_{\text{dyn}}/M_{\text{bary}}$ because we do not have the stellar mass for this galaxy. For a reasonable fraction of stellar mass, of the galaxies we can plot here, DDO 47 does have a high $M_{\text{dyn}}/M_{\text{bary}}$. Furthermore, there is a suggestion of a trend of a higher fraction of gas engaged in noncircular motions for higher $M_{\text{dyn}}/M_{\text{bary}}$, although with a lot of scatter.

We looked for the characteristic crinkle pattern in the mom1 maps of other LITTLE THINGS galaxies that had been identified as possibly barred from twisting of isophotes in V-band images (DDO 43, DDO 70, DDO 154, F564-V3, NGC 3738, WLM, Haro 36) as well as the rest of the sample in which bars were not suspected since weak bars are found in a large fraction of cosmological simulations of dwarfs (Marasco et al. 2018). We did not find the crinkle pattern in the velocity field that would be evidence of gas streaming motions in any of these galaxies.

3.2. Large-scale Filaments and Accretion

Simulations suggest that cold accretion of gas from the cosmic web onto galaxies is an ongoing process even today and a driver for ongoing star formation in spirals (e.g., Finlator & Davé 2008; Forbes et al. 2014; Sánchez Almeida et al. 2014). For example, Schmidt et al. (2016) found radial mass fluxes in five spiral galaxies from The H I Nearby Galaxy Survey (THINGS; Walter et al. 2008) that were comparable to their star formation rates (SFRs). Sánchez Almeida et al. (2015) find that large regions of star formation in tadpole galaxies are significantly lower in metallicity than the rest of the galaxy. They argue that these are possibly regions where accreting gas has been compressed as it enters the disk and a large star-forming event was triggered. Since the low metallicity gas rotates through the galaxy and dissipates in less than an orbital period, the accretion events must have happened recently for unusually low metallicity regions to be found.

Motivated by these observations, Ceverino et al. (2016) have run cosmological zoom-in simulations of the growth of a dIrr galaxy, tracking gas accretion and the distribution of star formation and metallicity in order to make connections between gas inflows and low metallicity regions in star-forming galaxies. They found that a number of their simulated galaxies have clumpy H$\alpha$ regions with lower metallicity than the rest of the galaxy, such as observed in the tadpole galaxies. In the simulations, the velocities of the incoming streams of gas differ significantly from the bulk motion of the galaxy, and terminate at the clumpy H$\alpha$ regions. This implies that the...
incoming gas streams are piling up and driving the high SFR, low metallicity pockets. To look for accretion events, therefore, we might expect to find incoming streams of gas that are more dense and moving at a different velocity than the bulk rotation of the existing HI disk. Furthermore, the impact of gas clouds on dIrrs has been observed to result in the formation of super star clusters (for example in NGC 1569 and NGC 5253; Johnson 2013; Turner et al. 2015). Thus, we might expect to find significant star-forming events to be associated with these streams.

Large filamentary structures were identified in two of our galaxies: DDO 47 and DDO 133. The filament in DDO 133 is region 18 in Figure 7, and region 17 just above region 18, although somewhat detached, could also be part of this filament. There are $2.7 \times 10^6 M_\odot$ of gas in this filament, which is 3% of the total HI mass of the galaxy. The width of the filament is about 590 pc, the average column density of the HI is $1.8 \times 10^{20}$ atoms cm$^{-2}$, and the distance of the filament from the center of the galaxy in the face-on plane of the galaxy is about 3 kpc. As an example, Figure 16 shows cuts through the HI cube at three positions in the filament: the middle of region 17, the middle of the north half of region 18, and the middle of the south half of region 18. The intensity peaks due to the bulk and snonc motion gas are marked, and there is also a
The fraction of H I gas engaged in strong noncircular motions vs. the log of the ratio of dynamical mass to baryonic mass $M_{\text{dyn}}/M_{\text{bary}}$ for each galaxy with analyzed noncircular motion regions. The dynamical mass comes from the rotation curve analysis by Oh et al. (2015) and includes all forms of mass. DDO 47 is shown as the red X. The upper limit on $M_{\text{dyn}}/M_{\text{bary}}$ for DDO 47 is due to the fact that we do not have a stellar mass for DDO 47.

Figure 15. Fraction of H I gas engaged in strong noncircular motions vs. the log of the ratio of dynamical mass to baryonic mass $M_{\text{dyn}}/M_{\text{bary}}$ for each galaxy with analyzed noncircular motion regions. The dynamical mass comes from the rotation curve analysis by Oh et al. (2015) and includes all forms of mass. DDO 47 is shown as the red X. The upper limit on $M_{\text{dyn}}/M_{\text{bary}}$ for DDO 47 is due to the fact that we do not have a stellar mass for DDO 47.

We examined the timescales for destruction of the filaments in DDO 133 and DDO 47. We first look at the rate of growth of shearing perturbations, given by Hunter et al. (1998) as $\pi G \Sigma_g / c$, where $G$ is the gravitational constant, $\Sigma_g$ is the gas surface density, and $c$ is the gas velocity dispersion. We multiply the H I surface density by 1.34 to include Helium. For the filament in DDO 133 we find that the growth rate is $5 \times 10^{-18}$ s$^{-1}$, which gives a timescale of $6 \times 10^9$ yr. Thus, it would take a very long time to destroy the filament by the growth of a shearing perturbation, if the filament is in the plane of the galaxy disk.

Next we consider the time for the filament to disperse, given the width and the velocity dispersion of the gas. The timescale to disperse (width divided by velocity dispersion) is $8 \times 10^7$ yr, which is 19% of an orbital time for the galaxy. This implies that dissipation may be the primary destruction mechanism for the filament in DDO 133. This is the predominant mechanism for destruction found in the simulations of Ceverino et al. (2016).

For the filament in DDO 47 we find the timescale for the growth of shearing perturbations is $8 \times 10^7$ yr and the timescale for dispersion is similar at $1 \times 10^8$ yr. The latter is 31% of an orbital time. Thus the filament in DDO 47 could be destroyed by either shearing perturbations or dissipation.

Finally, we consider whether the filament in DDO 133 is unstable to gravitational instabilities that might enable it to collapse into star-forming clouds. The H I plus He gas density is $2.4 \times 10^{20}$ atoms cm$^{-2}$. This gas density is 20% of the Toomre (1964) critical gas density for instability at that radius in DDO 133 (Elmegreen & Hunter 2015). A typical region in the filament in DDO 47 has an H I+He column density of moving around 240 km s$^{-1}$ along the line of sight, while there is even more gas there moving in noncircular motion at about 253 km s$^{-1}$. The width of the filament is about 760 pc, the average column density of the H I is $4.7 \times 10^{20}$ atoms cm$^{-2}$, and the distance of the filament from the center of the galaxy in the plane of the galaxy is about 4 kpc. As for DDO 133, there is no connection between young regions seen in FUV or H$\alpha$ and the filament.

The filament in DDO 47 is less coherent and is delineated by regions 9–12 (and possibly region 8) in Figure 2. The gas in the filament is $5.3 \times 10^6 M_\odot$, which is 1% of the total H I mass of the galaxy, and has median velocities of 4–8 km s$^{-1}$ higher than in the nearby bulk rotation gas. An example of a cut through the H I cube at a point in the middle of region 11 is shown in Figure 17. The gas in bulk motion at that location is

**Figure 14.** DDO 47. The solid arc in each panel traces the crinkle pattern in the velocities. Top: false-color image velocity field (mom1). The long black solid straight line and shorter line perpendicular to that mark the major and minor axes of the galaxy from fits to the H I velocity field by Oh et al. (2015). Ten white velocity contours from 230 to 310 km s$^{-1}$ are superposed. Color bar units are km s$^{-1}$. Middle: false-color image of the integrated H I intensity (mom0). The color bar units are Jy beam$^{-1}$ m s$^{-1}$. Bottom: false-color V-band image. The color bar units are the same as in Figure 2. A stellar bar is not obvious; the small structure in the center (colored red) is largely associated with star formation (see the FUV image in Figure 2).
6.3 × 10^{20} \text{ atoms cm}^{-2}, and this is 47\% of the Toomre critical gas density. Therefore, the filaments are stable against internal collapse into self-gravitating clouds.

As to whether either of these filaments could be cosmic cold accretion, we cannot tell for sure. However, the filaments that we observe are fairly well behaved, being nearly engaged in the rotation pattern of the galaxy. By contrast, a cloud of gas falling onto the BCD VII Zw 403 has a very complex kinematic pattern relative to the body of the galaxy (see Figure 17 in Ashley et al. 2017). The simulations of cold accretion in dwarf galaxies by Ceverino et al. (2016; see their Figure 4) also show significant deviations in the velocities of the infalling gas relative to the galaxy. Furthermore, there does not seem to be consequences of these filaments to the galaxies in terms of star formation. While the observational signatures of accretion might depend on the details of the infall and on the density of the gas it is falling onto, it seems that these filaments, whatever their nature, are not having much of an impact on their host galaxies. By the same argument and the fact that these galaxies were chosen to be fairly isolated, it seems unlikely that these filaments are the consequence of a recent interaction with another galaxy. However, transient instability modes, as discussed for DDO 47 above, are possibilities.

3.3. Relationship of Noncircular Motion Gas to Star Formation

We plot the SFR surface density of each galaxy against the ratio of mass of H I in that galaxy engaged in significant noncircular motion to the total HI mass of the galaxy. This is shown in Figure 18 with the SFR surface density determined from FUV emission on the left and that from H\(\alpha\) on the right. Galaxies without gas engaged in noncircular motions (at \(M_{\text{snonc}}/M_{\text{HI tot}} = 0\)) cover the full range of SFRs, but for the rest of the galaxies there is a slight decrease in FUV SFR surface density with increasing \(M_{\text{snonc}}/M_{\text{HI tot}}\), although this is not evident for the H\(\alpha\) SFR surface density. The FUV trend is opposite to the expectation that noncircular motions might facilitate star formation. On the other hand, if the presence of large amounts of snonc gas results in starbursts that are short lived, we might be less likely to catch those events.

On a local level, too, there is no pattern of correspondence between star-forming regions and strong noncircular motion gas. Generally speaking, in a given galaxy, a few noncircular motion regions might be coincident with FUV or H\(\alpha\) emission, but other regions are not and there can be lots of star formation in a galaxy not connected to gas moving differently from the bulk rotation.
3.4. Relationship of Noncircular Motion Gas to Holes

Holes in the HI gas of the LITTLE THINGS dwarfs have been cataloged by Pokhrel (2016; see Bagetakos et al. 2011 for the methodology in identifying the holes). As an example, in Figure 19 we plot the location of the eight holes in DDO 133 and compare those to the location of snonc and wnonc features. We see that three of the gas holes overlap with snonc features. The most interesting hole is number 3, which overlaps with snonc region 9 and is adjacent to the northeast corner of the stellar bar and to the east of the northern part of a wnonc feature at the end of the bar (large red area in the bottom panel of Figure 19). Expansion of the shell around hole 3 might have contributed to the snonc and wnonc features, although currently the hole has blown out of the disk and is not expanding (Pokhrel 2016). Hole number 5 also appears to be connected with wnonc gas seen in the bottom panel of Figure 19 and snonc region number 13, and hole number 4 overlaps with snonc region 12.

3.5. Relationship of Noncircular Motion Gas to Velocity Dispersion

In the bottom right panels of Figures 1–11 we plot the snonc features on the H I velocity dispersion (mom2) maps of the galaxies. Here we are looking for correlations between the snonc features with velocity dispersion that would indicate that these motions generate excess turbulence. Ashley et al. (2014), for example, found excess turbulence at the impact points of accreting gas in IC 10. In most galaxies there are some snonc features in regions at the upper range of turbulence values in the galaxy. For example, in CVnIdwA both regions are adjacent to the two regions of higher velocity dispersion (red in the mom1 map in Figure 1). Other snonc regions are located in the central parts of the galaxies where the velocity dispersion is overall higher, as in DDO 47 (Figure 2), and the association is not likely specific to the snonc nature of the regions; the higher velocity dispersion regions are located throughout the galaxy and the snonc regions appear to be randomly associated, as in DDO 70 (Figure 5). Thus, generally there is no systematic correlation between snonc regions and regions of high velocity dispersion.

However, there are two exceptions of note. In DDO 168 (Figure 8), all of the snonc features are located on the eastern edge of a large part of the galaxy where the velocity dispersion exceeds 14 km s⁻¹. There is nothing obviously unusual in that region of the galaxy at other wavelengths, so it is not clear why this large section of the galaxy has such a high velocity dispersion. In DDO 210 (Figure 9), just outside the snonc regions to the northeast and southeast are areas where the velocity dispersion of the gas is >11 km s⁻¹. These high
velocity dispersion regions line the edges of the large-scale arc structures.

4. Summary

We have examined maps of the gas engaged in noncircular motions in 22 of the LITTLE THINGS sample of nearby dIrr galaxies. The H\textsc{i} data cubes have been deconvolved into H\textsc{i} in ordered bulk motions, H\textsc{i} engaged in noncircular motions that has higher intensity peaks than the underlying bulk motion gas (snonc), and H\textsc{i} engaged in noncircular motions that has lower intensity peaks than the underlying bulk motion gas (wnonc). Maps of these kinematic components consist of integrated moment 0, velocity field moment 1, and velocity dispersion moment 2 maps. We found significant regions of snonc motion gas in half of the galaxies.

In DDO 133 we found a crinkle pattern in the velocity field isophotes that is characteristic of streaming motions around the obvious stellar bar potential seen in the optical. In addition, concentrations of gas engaged in noncircular motions and star-forming regions are found at the northern end of the bar. The same velocity field pattern is found in DDO 47, but no stellar bar is obvious.

DDO 47 and DDO 133 also have large-scale filamentary structures found in the outer disks with strong noncircular motions. Neither filament is connected with any star-forming regions. These filaments could be transient instabilities in the gas. Given the timescales, the likely mechanism for destruction of the filament in DDO 133 is dispersion due to the velocity dispersion of the gas. The destruction mechanism in DDO 47 could be either dispersion or shearing perturbations.

We compared the location of noncircular motion gas features with the location of star-forming regions. We only see a correlation at the northern end of the bar in DDO 133, where streaming motions of the gas around the bar has probably facilitated cloud formation. There is no correlation between the integrated galactic SFR surface density and the ratio of gas mass engaged in noncircular motion to total H\textsc{i} mass of the galaxy or on a local scale between holes in the gas and snonc gas. In most cases the snone gas is not spatially related to an enhancement in the gas velocity dispersion. However, there is an unusual correlation of snone gas in DDO 168 and a large portion of the galaxy with higher velocity dispersion in the gas than elsewhere in that galaxy.

L.L. appreciates funding from the National Science Foundation grant AST-1461200 to Northern Arizona University for Research Experiences for Undergraduates summer internships and Dr. David Trilling for running the NAU REU program in 2018. We wish to thank Dr. Michael West for discussions in the early stages of this project. Obtaining and reducing the LITTLE THINGS data that were used here were funded in part by the National Science Foundation through grants AST-0707563, AST-0707426, AST-0707468, and AST-0707835 to US-based LITTLE THINGS team members and with generous technical and logistical support from the National Radio Astronomy Observatory.

Facility: VLA.

ORCID iDs
Deirdre A. Hunter @ https://orcid.org/0000-0002-3322-9798
Se-Heon Oh @ https://orcid.org/0000-0002-5648-9920
Stephen E. Levine @ https://orcid.org/0000-0002-1050-3539
Caroline E. Simpson @ https://orcid.org/0000-0003-3015-7300

References
Ashley, T., Elmegreen, B., Johnson, M., et al. 2014, AJ, 148, 130
Ashley, T., Simpson, C. E., Elmegreen, B. G., Johnson, M., & Pokhrel, N.-R. 2017, AJ, 153, 132
Bagetakos, I., Brinks, E., Walter, F., et al. 2011, AJ, 141, 23
Barnes, K., van Zee, L., Côté, S., & Schade, D. 2012, ApJ, 757, 64
Bigiel, F., Leroy, A., Walter, F., et al. 2010, AJ, 140, 1194
Boldrini, P., Mohayaee, R., & Silk, J. 2019, MNRS, 485, 2546
Bosma, A. 1981, AJ, 86, 1825
Ceverino, D., Sánchez Almeida, J., Muñoz Tuñón, C., et al. 2016, MNRS, 457, 2605
Elmegreen, B., & Hunter, D. 2015, ApJ, 805, 145
Finlator, K., & Davé, R. 2008, MNRS, 385, 2181
Forbes, J. C., Krumholz, M. R., Burkert, A., & Dekel, A. 2014, MNRS, 438, 1552
Gallagher, J. S., & Hunter, D. A. 1984, AJ, 22, 37
Gentile, G., Burkert, A., Salucci, P., Klein, U., & Walter, F. 2005, ApJL, 634, L145
Herrmann, K. A., Hunter, D. A., & Elmegreen, B. G. 2013, AJ, 146, 104
Hunter, D. A., & Elmegreen, B. G. 2004, AJ, 128, 2170
Hunter, D. A., & Elmegreen, B. G. 2006, ApJS, 162, 49
Hunter, D. A., Elmegreen, B. G., & Baker, A. L. 1998, ApJ, 493, 595
Hunter, D. A., Elmegreen, B. G., & Lidka, B. C. 2010, AJ, 139, 447
Hunter, D. A., Ficut-Vicas, D., Ashley, T., et al. 2012, AJ, 144, 134
Johnson, J. M. 2013, AJ, 145, 146
Levine, S. E., & Sparke, L. S. 1994, ApJ, 428, 493
Lin, L.-H., Wang, H.-H., Hsieh, P.-Y., et al. 2013, ApJ, 771, 8
Marasco, A., Oman, K. A., Navarro, J. F., Frenk, C. S., & Oosterloo, T. 2018, MNRS, 476, 2168
Oh, S.-H., de Blok, W. J. G., Walter, F., Brinks, E., & Kennicutt, R. C., Jr. 2008, AJ, 136, 2761
Oh, S.-H., Hunter, D., Brinks, E., et al. 2015, AJ, 149, 180
Oman, K. A., Marasco, A., Navarro, J. F., et al. 2019, MNRS, 482, 821
Pokhrel, N. R. 2016, PhD Dissertation, Florida International Uni.
Read, J. I., Iorio, G., Agertz, O., & Fraternali, F. 2016, MNRS, 462, 3628
Sánchez Almeida, J., Elmegreen, B. G., Muñoz-Tuñón, C., et al. 2015, ApJL, 810, L15
Sánchez Almeida, J., Elmegreen, B. G., Muñoz-Tuñón, C., & Elmegreen, D. M. 2014, A&ARv, 22, 71
Schmidt, T. M., Bigiel, F., Klessen, R. S., & de Blok, W. J. G. 2016, MNRS, 457, 2642
Toomre, A. 1964, ApJ, 139, 1217
Turner, J. L., Beck, S. C., Benford, D. J., et al. 2015, Natur, 519, 331
Walter, F., Brinks, E., de Blok, W. J. G., & Joggerst, C. 2008, AJ, 136, 2563
Zhang, H.-X., Hunter, D. A., Elmegreen, B. G., Gao, Y., & Schruba, A. 2012, AJ, 143, 47