THE NEXT GENERATION VIRGO CLUSTER SURVEY. IV. NGC 4216: A BOMBARDED SPIRAL IN THE VIRGO CLUSTER

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ABSTRACT

The final stages of mass assembly of present-day massive galaxies are expected to occur through the accretion of multiple satellites. Cosmological simulations thus predict a high frequency of stellar streams resulting from this mass accretion around the massive galaxies in the Local Volume. Such tidal streams are difficult to observe, especially in dense cluster environments, where they are readily destroyed. We present an investigation into the origins of a series of interlaced narrow filamentary stellar structures, loops and plumes in the vicinity of the NGC 4216/NGC 4217 system, using the MegaPrime/MegaCam images obtained as part of the Next Generation Virgo Cluster Survey (NGVS). We confirm the previously identified features and identify a few additional structures. The NGVS data allowed us to make a physical study of these low surface brightness features and investigate their origin. The likely progenitors of the structures were identified as either already cataloged Virgo Cluster Catalog dwarfs or newly discovered satellites caught in the act of being destroyed. They have the same g − i color index and likely contain similar stellar populations. The alignment of three dwarfs along an apparently single stream is intriguing, and we cannot totally exclude that these are second-generation dwarf galaxies being born inside the filament from the debris of an original dwarf. The observed complex structures, including in particular a stream apparently emanating from a satellite of a satellite, point to a high rate of ongoing dwarf destruction/accretion in the region of the Virgo Cluster where NGC 4216 is located. We discuss the age of the interactions and whether they occurred in a group that is just falling into the cluster and shows signs of the so-called pre-processing before it gets affected by the cluster environment, or in a group which already ventured toward the central regions of Virgo Cluster. In any case, compared to the other spiral galaxies in the Virgo Cluster, but also to those located in lower density environments, NGC 4216 seems to suffer an unusually heavy bombardment. Further studies will be needed to determine whether, given the surface brightness limit of our survey, about 29 mag arcsec−2, the number of observed streams around that galaxy is as predicted by cosmological simulations or conversely, whether the possible lack of similar structures in other galaxies poses a challenge to the merger-based model of galaxy mass assembly.

Key words: galaxies: clusters: individual (Virgo) – galaxies: dwarf – galaxies: evolution – galaxies: interactions

Online-only material: color figures

1. INTRODUCTION

Dwarf galaxies play a key role in ΛCDM large-scale structure formation scenarios (e.g., Dekel & Silk 1986; Navarro et al. 1996). Indeed, according to this model, the dominant process of galactic growth is the accretion of small galaxies, and the large stellar halos found around massive galaxies such as our own Milky Way have been assembled thanks to the infall of (and merging with) many small dwarf galaxies (Bullock & Johnston 2005). Prior to their capture, dwarf galaxies are often disrupted through large tidal forces generated by their host galaxies, which form stellar streams and shells around their hosts (see review by Duc 2012, and references therein). Although such fine structures...
have a lifetime of a few Gyr in isolated environments, they are much shorter lived in dense cluster environments, where they interact with the cluster potential and are quickly dispersed out (Mihos 2004; Tal et al. 2009; Adams et al. 2012). Disrupted satellites may also be contributing stars to the intracluster light (ICL), where the debris generated by numerous interactions over the lifetime of the cluster is observed as a vast diffuse halo around the most massive galaxies (Rudick et al. 2009; Mihos et al. 2005; Janowiecki et al. 2010). On the other hand, the cores of tidally stripped galaxies of intermediate mass may become compact ellipticals (cEs), and the nuclei of tidally stripped dwarfs may become ultracompact dwarf galaxies (Sasaki et al. 2007; Forbes et al. 2003; Huxor et al. 2011). The scenario is commonly known as tidal threshing (Bekki et al. 2003).

Because of their being stretched out, disrupted dwarf galaxies experience a strong dimming of their surface brightness and become very difficult to detect. Until recently, very few candidate “disrupted dwarfs” were known outside of the Local Group. With the advent of sophisticated instruments and the development of data analysis techniques optimized to detect low surface brightness (LSB) structures, the number of detections is growing (Forbes et al. 2003; Martín-Delgado et al. 2009, 2010; Duc et al. 2011; Miskolczi et al. 2011; Koch et al. 2012). However, most of the observed features—filaments, warps, plumes, and shells—are leftovers from rather old collisions, as their progenitors are no longer visible or identifiable. The deep imaging survey of nearby spirals carried out by Martín-Delgado et al. (2010) with robotic facilities such as the 0.5 m Blackbird telescope shows a number of cases of dwarf galaxies currently undergoing tidal disruption. These include a pair of dwarf satellites of the Virgo spiral galaxy NGC 4216 which are associated with extended tidal tails, whose brightest parts, cataloged as independent dwarf galaxies in Virgo Cluster Catalog (VCC; Binggeli et al. 1985), are visible on shallower Sloan Digital Sky Survey (SDSS) images (Miskolczi et al. 2011).

In this paper, we revisit this system, using images obtained as part of the Next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012). The excellent image quality of the survey allowed us to disclose new objects, especially a couple of filaments and disrupted dwarfs, and to perform a surface photometry and color analysis.

NGVS observations and data reduction are presented in Section 2. The results, in particular the photometric properties of the newly discovered features, are detailed in Section 3. In Section 4, we investigate the origin of the streams, their age and fate. From a global view provided by the NGVS, we consider the overall uniqueness of the NGC 4216 system within the Virgo Cluster.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out as part of the NGVS deep imaging survey using the MegaCam instrument (Boulade et al. 2003) on the 3.6 m Canada–France–Hawaii Telescope (CFHT). The observational strategy, data reduction procedure, and data quality control are described in Ferrarese et al. (2012). In brief, the multi-band NGVS survey benefits from the very wide field of view of the camera (∼1° x 1°), and its very good image quality (0′′6–0′′9) obtained through optimizing the observing conditions. The images are processed with a dedicated data reduction pipeline, Elixir-LSB, which is explicitly designed to optimize the detection of very LSB structures such as ICL, faint stellar streams, and ultra-faint dwarf galaxies (Magnier & Cuillandre 2004; J. C. Cuillandre et al., in preparation). The output products of Elixir-LSB are single frames and stacks in which the sky background has been modeled and removed (Gwyn 2008; S. D. J. Gwyn et al., in preparation). Further image analysis has been done using standard routines of IRAF and IDL.

For the study, we made use of NGVS images obtained in the g′, i′, and z′ bands. Total exposure times were 0.88, 0.57, and 1.2 hr, respectively. Since the g-band image is the most sensitive and the cleanest, i.e., it contains the least number of artifacts such as CCD imprints and reflection halos (see below), it was preferentially used for our photometric analysis.

Surface photometry of very LSB objects is notoriously difficult. The precision of their measured parameters is affected by several factors, including the accuracy of the photometric calibration, sky background variation, and artifacts due to imperfect optics. The photometric calibration of the NGVS has been done using the SDSS photometry with a level of accuracy corresponding to a 1% variation in the photometric zero point (see Ferrarese et al. 2012). At the surface brightness limit of the survey (29 mag arcsec−2 in the g band), the main limitations to the LSB structure analysis and photometry are due to the reflection halos around the bright sources (stars but also the nuclei of bright galaxies with steeply rising surface brightness profiles), which show up as large disks that cannot easily be removed from the images (see an example of one of these halos in the upper left corner of Figure 1). We therefore exclude in our analysis the contaminated areas where reflected light becomes dominant over the actual LSB feature.

Foreground stars and compact background galaxies were removed by applying a ring filter to the images, and residuals were manually subtracted with the IRAF task imedit. The apertures used to carry out the photometry of the faint filaments and plumes, shown in Figure 2, were defined visually as their surface brightness is too low for an automatic detection. The errors in the photometric measurements are to a large extent determined by those in the sky determination. Although a master sky background is subtracted from each image, for our aperture photometry measurements we sampled the sky background at multiple positions around the targets. The number of sky probes ranged between 5 and 100, depending on the size of the objects. Each individual sky region consisted of 20 x 20 pixel boxes. The median value and errors were then computed.

3. RESULTS

3.1. NGC 4216 and Its Environment

Figure 1 shows a composite MegaCam image of the field around NGC 4216 (cf. Figure 1(c) in Martín-Delgado et al. 2010). The regions with the highest surface brightness are displayed in “true color” (combination of g′-, i′- and z-band images) while for the LSB regions, a monochromatic g-band image is shown.

NGC 4216 is a barred spiral galaxy—it is classified as SAB(s)bc in the RC3 catalog (de Vaucouleurs et al. 1991)—located in the outskirts of the Virgo Cluster at an angular distance of ∼4° from the cluster center, M87. It is

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13 Image Reduction and Analysis Facility software is distributed by National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

14 Noted as g, i, and z in the rest of the paper.

15 The virial radius of Virgo’s A subcluster, centered on M87, is 5:4 (McLaughlin 1999).
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Figure 1. Composite NGVS image of the field around NGC 4216. A monochromatic g-band image for which the faintest point-like stars have been subtracted is shown with a gray scale. For regions above a surface brightness level $\sim 24$ mag arcsec$^{-2}$, and in empty sky regions far from the main galaxy, a true color image (composite of g-, i-, z-band images) is superimposed. North is up, east is left, and the field of view is 20 $\times$ 17 arcmin. The image in the inset on the upper right corner is a zoom toward VCC 165, the closest companion of NGC 4216. (A color version of this figure is available in the online journal.)

an edge-on orientation with an inclination angle $i = 85^\circ$. As shown in Figure 1, its central regions are characterized by a prominent dust lane (Chung et al. 2009) and a red and compact bright nucleus. The galaxy is surrounded by a very diffuse stellar halo, and complex filamentary structures, including streams and plumes. The investigation of their nature is the focus of this study.

The H$\alpha$ map of NGC 4216 from the Very Large Array (VLA; Chung et al. 2009) indicates an H$\alpha$ extent which is somewhat smaller than in the optical: the ratio of the H$\alpha$ and optical B-band radii, measured, respectively, at the 1 $M_\odot$ pc$^{-2}$ H$\alpha$ surface density level and the 25 mag arcsec$^{-2}$ isophotal level in the $B$ band, is $D_{H\alpha}^{iso}/D_B = 0.76$.

The low radial velocity of NGC 4216 (131 km s$^{-1}$, which is significantly offset relative to the $\sim 1300$ km s$^{-1}$ mean velocity of the cluster itself) indicates that it is moving relatively fast with respect to the cluster center. It is the most massive galaxy within a circle of 400 kpc projected radius; the nearest galaxy of higher mass is M99 at a projected distance of 420 kpc. Within that field of view, there are two early-type galaxies, and five late-type star-forming galaxies with radial velocity differences less than $\pm 300$ km s$^{-1}$ with respect to that of NGC 4216. The

| Galaxy   | R.A.  | Decl. | $M_B$  | $V$   | $d$  | Morph. |
|----------|-------|-------|--------|-------|------|--------|
| NGC 4216 | 183.976 | 13.149 | −20.2 | 131   | ⋯    | Sb(s)  |
| NGC 4222 | 184.093 | 13.307 | −17.1 | 230   | 56.5 | Scd    |
| VCC 165  | 183.972 | 13.215 | −15.6 | 255   | 19.2 | S01    |
| VCC 200  | 184.140 | 13.031 | −15.8 | 16    | 58.0 | dE2, N |
| VCC 197  | 184.136 | 13.162 | −11.5 | ⋯    | 46.0 | dE1    |
| VCC 185  | 184.083 | 13.137 | −10.9 | ⋯    | 31.0 | dE1    |

Notes. The coordinates, heliocentric radial velocities, $V$, and morphologies are from NED. The absolute B-band magnitudes are derived from the B-band magnitudes listed in the Goldmine database (http://goldmine.mib.infn.it). An average distance for the Virgo Cluster of 16.5 Mpc (corresponding to 80 pc arcsec$^{-1}$) was assumed, and $d$ is the projected distance on the sky from the center of NGC 4216.

basic properties of NGC 4216 and its closest companions are listed in Table 1. In the close vicinity of NGC 4216, toward the north lies VCC 165, at a projected distance of 19.2 kpc. VCC 165 is classified by Binggeli et al. (1985) as an S0$_1$ galaxy. Another
Figure 2. Identification of the principal companion galaxies, stellar streams, plumes, and progenitor candidates around NGC 4216. The apertures used to carry out the photometry are delineated on the displayed g-band image. Note that for objects A, B, and C, the boundaries correspond to a surface brightness of 27.3 mag arcsec$^{-2}$, the average surface brightness of filament F1. G1 and G2 are two selected regions in the extended stellar halo of NGC 4216. The dashed line near the extended stellar halo represents a possible, but not yet proven, connection between F1 and F2.

On our deep images, the stellar halo of the galaxy NGC 4222 overlaps with the reflection halo of a bright star. Southeast of NGC 4216, at 58.0 kpc distance from its center, at a similar radial velocity, lies a nucleated early-type dwarf galaxy VCC 200 (Côté et al. 2006). All these companions are identified on Figure 2.

3.2. The Streams Around NGC 4216

Figure 2 identifies the main streams and remnants of dwarf galaxies in the vicinity of NGC 4216 and VCC 165. The NGVS images clearly show the main long filament F1, which was first detected by Martínez-Delgado et al. (2010). We also see the fainter structures present on the deep optical image of Martínez-Delgado et al. (2010) such as the bend in F1 toward its eastern tip, the long narrow filament to the north of the system (F2) and the plume-like filaments that stick out east of NGC 4216 (F5 and F6). Besides these previously known structures, new features are detected, such as a filament apparently wrapping around VCC 165 (F4), a loop east of NGC 4216 (F3), and a possible bridge between NGC 4216 and VCC 200 (F7).

With respect to previous surveys, the gain in spatial resolution provided by CFHT/MegaCam allows us to identify the dwarf galaxies presumably at the origin of these filaments. Finally, the photometric calibration precision of the multi-band NGVS allowed us to determine the photometric properties and colors of these various features, which so far had not been possible. The photometric data on the streams and progenitors are presented, respectively, in Tables 2 and 3.

The most prominent tidal stream, F1, east of NGC 4216, has an angular extent of ∼12.5 arcmin on the sky, which corresponds to ∼60 kpc at the assumed mean distance of the cluster, 16.5 Mpc (Mei et al. 2007). The filament starts from the southeast corner of NGC 4216 and near its easternmost tip it makes a sudden turn toward the west–north with an angle of about 120°. Although further away it gets lost within the halo of a bright red star, when it emerges again, it seems to join the filament F2, the second longest filament in the field, north of NGC 4216. Unfortunately, the stellar halo glare in the region between the two filaments does not allow us to say with certainty that a physical connection exists. No such bridge is visible on the slightly shallower image of Martínez-Delgado et al. (2010), where the stellar halo is less intrusive. The width of the stellar stream F1 appears constant along most of its length, about ∼3 kpc. It broadens after the bend. As shown in Figures 3 and 4, the average surface brightness of the filament (excluding regions close to the dwarf galaxies along it) is slightly below 28 mag arcsec$^{-2}$.

The NGVS image discloses another rather broad stream, F3, with a surface brightness below 28.5 mag arcsec$^{-2}$ (see Figure 3), which sticks out of NGC 4216, then bends to cross filament F1 and finally falls back toward the host galaxy, near F7.
Figure 3. $g$-band surface brightness map of the field around NGC 4216. The surface brightness scale in mag arcsec$^{-2}$ is shown to the right and the field of view is the same as for Figure 2. The white contour corresponds to the faintest level of 21 cm H\textsc{i} line emission in NGC 4216 detected with the VLA by Chung et al. (2009).

Figure 4. Variation of the median $g$-band surface brightness along the length of filament F1, from dwarf galaxy C near NGC 4216 to its easternmost tip where it gets lost within the halo of a star. Photometric measurements were obtained collapsing the filament along its width and median-combining the data. The positions of the dwarf galaxies A, B, and C (see Figure 2) are indicated.

The very broad filament F7 points in the direction of the dwarf companion VCC 200, but a physical connection between the two galaxies cannot be firmly established. The plume-like stellar structures which apparently stick out from the main body of NGC 4216 on its western side (F5 and F6) may in fact be filaments which connect to F1–F3 behind the galaxy. They have a nearly uniform surface brightness of 27.5 mag arcsec$^{-2}$.

Other filamentary structures can be seen (see labelling on Figure 2) around VCC 165, the closest companion of NGC 4216. On the displayed $g$-band image, a model of VCC 165 obtained with the IRAF task \texttt{bmodel} has been subtracted to further enhance the filaments. The most prominent one, the 6 kpc long structure labeled F4, wraps around the dwarf companion on one side, and points toward the galaxy center on the other. There is a further hint that the galaxy extends further toward the east in the direction of the spiral. VCC 165 itself, despite its apparent proximity to NGC 4216, does not exhibit strong signs of morphological perturbation. The map obtained subtracting the ellipse model (see Figure 5) does not show prominent residuals in its outer regions. In the inner regions, spiral-like features (or narrow dust lanes) may be observed.

We measured the $g - i$ colors for the most prominent features. The $i$-band photometric measurements were particularly delicate as this band shows several residuals at LSB levels, such as chip gaps. The contamination by stellar halos is also more severe in this band. Even the nucleus of NGC 4216 generates an artificial, disk-like structure with a radius of nearly 3 arcmin, which is almost invisible in the $g$ band, but becomes noticeable in the $i$ and $z$ bands. Regions affected by the stellar or galactic reflection halos were excluded from our analysis. The colors are listed in Table 2. The $g - i$ color for F1 is uniform along its length and has an average value $g - i = 0.9 \pm 0.1$ mag. Interestingly, this value agrees, within the errors, with that of filament F2, possibly suggesting a common physical origin for the two.
ellipticities \( e \) and the standard Johnson system using the calibration of Jordi et al. (2006) and assuming a distance of 16.5 Mpc (Mei et al. 2007). The stellar masses, \( M_\ast \), were estimated from the extrapolated absolute magnitudes assuming the mass to light ratios of Bell et al. (2003).

### Table 2

Properties of the Filaments (F1–F7) and External Halo Regions (G1–G2) of NGC 4216

| Feature | \( g - i \) (mag) | \( \langle \mu_g \rangle \) (mag arcsec\(^{-2} \)) | \( M_B \) (mag) | \( \log(M_\ast) \) (\( M_\odot \)) |
|---------|----------------|---------------------|----------------|-------------------|
| F1      | 0.9 ± 0.1      | 27.8 ± 0.1          | −14.2          | 8.2               |
| F2      | 0.7 ± 0.1      | 26.7 ± 0.1          | −12.2          | 7.1               |
| F3      | ···            | 28.6 ± 0.5          | −13.5          | 7.8               |
| F4      | 1.1 ± 0.1      | 25.8 ± 0.1          | −10.0          | 6.9               |
| F5      | 0.7 ± 0.2      | 27.1 ± 0.1          | −13.0          | 7.5               |
| F6      | 0.8 ± 0.1      | 26.9 ± 0.1          | −13.0          | 7.6               |
| F7      | 1.0 ± 1.0      | 27.4 ± 0.2          | −14.2          | 8.2               |
| G1      | 0.8 ± 0.1      | 26.0 ± 0.1          |                |                   |
| G2      | 0.7 ± 0.1      | 26.4 ± 0.1          |                |                   |

Notes. The color \( g - i \) was determined from aperture photometric measurements in areas not contaminated by instrumental artifacts. \( \langle \mu_g \rangle \) is the average surface brightness within the areas defined in Figure 2, excluding the progenitors (i.e., A, B, and C). The associated errors are computed from the standard deviation of the individual sky background measures. The absolute blue magnitude in the \( B \) band, \( M_B \), was derived from the extrapolated observed magnitude, i.e., the average surface brightness times the area, converting the MegaCam magnitudes to the standard Johnson system using the calibration of Jordi et al. (2006) and assuming a distance of 16.5 Mpc (Mei et al. 2007). The stellar masses, \( M_\ast \), were estimated from the extrapolated absolute magnitudes assuming the mass to light ratios of Bell et al. (2003).

### Table 3

Properties of the Dwarf Galaxies Identified Along the Filaments

| Object       | \( M_B \) (mag) | \( g - i \) (mag) | \( e \) | \( \log(M_\ast) \) (\( M_\odot \)) | \( R_e \) (kpc) |
|--------------|----------------|----------------|------|-------------------|--------------|
| (A) VCC 197  | −12.1          | 0.88 ± 0.02    | 0.79 | 7.2               | 4.5          |
| (B) VCC 185  | −10.2          | 0.86 ± 0.02    | 0.29 | 6.7               | 0.4          |
| C            | −09.6          | 0.62 ± 0.04    | ···  | 6.0               | 0.3          |
| D            | −11.3          | 1.05 ± 0.02    | ···  | 7.1               | ···          |
| (N)          | −07.0          | 1.05 ± 0.04    | 0.63 | 5.3               | ···          |
| VCC 165      | −15.5          | 1.22 ± 0.01    | 0.15 | 8.9               | 1.3          |

Notes. The absolute blue magnitude and colors were determined from photometric measurements made within the apertures defined in Figure 2. The ellipticities \( e \) were derived using the IRAF ellipse task. The effective radius \( R_e \) is derived with a two-dimensional fitting of the light profile with a Sérsic model made with GALFIT (Peng et al. 2002). D is the disrupted dwarf galaxy near VCC 165 (see Figure 6), while N is its candidate nucleus.

### 3.3. Stellar Cores within the Filaments

Several objects of higher surface brightness are visible toward the streams: such cores are likely the remnants of tidally disrupted dwarf galaxies and as such appear as good progenitor candidates of the filaments’ stellar material.

As shown in Figures 2 and 3, the most extended filament, F1, hosts three relatively compact stellar objects. The most luminous object, A, is also the most extended (see Figure 5). It has a \( \sim 24.5 \) mag arcsec\(^{-2} \) central \( g \)-band surface brightness, which in principle is high enough to have it included in the VCC (VCC 197). Modeling the galaxy with ellipses (using the IRAF task ellipse and bmodel), we found that it is stretched out along filament F1 and contains a bar-like structure along the minor axis, and a compact nucleus. Modeling the galaxy with a Sérsic model with GALFIT (Peng et al. 2002), we obtained a best fit with an exponential profile and a very large effective radius of \( \sim 5 \) kpc, a consequence of the tidal threshing.

Object B—also in the VCC (VCC 185)—with an effective radius of 0.4 kpc and an ellipticity of 0.29, is more compact and rounder. Although located at the crossing of filaments F1 and F3, its major axis is aligned with neither of these streams. Finally, object C is an uncataloged faint dwarf located near the base of the tail. It has a round shape and does not show any clear evidence of a tidal interaction. The integrated \( g - i \) colors of both A and B are in very good agreement with that of filament F1, while C is 0.2 mag bluer. Given their rather red colors, none of the galaxies show evidence of containing young stars. A is not detected on a deep 2600 s archival GALEX/NUV image (Boselli et al. 2011), while B shows very weak UV emission. At Arecibo, the ALFALFA HI survey (Haynes et al. 2011) did not detect any atomic hydrogen emission toward the three passive dwarfs. The much deeper AGES fields did not cover the NGC 4216 area (Taylor et al. 2012a, 2012b).

The brightest condensation along filament F4, west of VCC 165, turns out to be a chance superposition of a background low-mass active galactic nucleus (AGN) at a redshift of 0.043,
according to its SDSS spectrum. The second brightest object in that region is an extended structure that lies in the continuation of F4. Given its much higher surface brightness than that of the filament (see Figures 6 and 7), we argue here that it could be in fact the main-body remnant of an almost completely disrupted dwarf, which we have labeled as D. The fact that D and F4 have similar colors is consistent with this hypothesis. A small compact central core, labeled as N, can be seen toward D; it has the same color and could be the nucleus of the latter. The $B$-band absolute magnitude of $D$—see Figures 5 and 6—is $-11.3$ mag, i.e., in between that of dwarfs A and B.

The mass of the stars still bound to the dwarfs (A+B+C+D) amounts to less than one-tenth of the total stellar mass of the filaments (F1–F7). Assuming that all the stellar material in filament F1 was pulled out from galaxy A, then the galaxy must originally have had an absolute magnitude of $M_B = -15.6$ mag, a value in the range of bright early-type dwarf galaxies in the Virgo Cluster (Lisker et al. 2007).

4. DISCUSSION

In the Carnegie Atlas of Galaxies (Sandage & Bedke 1994), the spiral galaxy NGC 4216 is described as “one of the most famous galaxies in the sky because it is often used in textbooks to illustrate the bulge, disk, dust content, and spiral pattern of typical luminous galaxies near the middle of the Sb classification sequence.” The deep NGVS images we have presented here show many additional features around this prototypical galaxy, in particular a complex network of interlaced plumes, streams, and filaments. Although a detailed interpretation is not straightforward, the large number of LSB stellar tails is consistent with predictions from numerical simulations about the mass assembly of galaxies (Johnston et al. 2001; Bullock & Johnston 2005). This raises the question why all massive galaxies do not show a similar level of fine structures. In the following, we propose scenarios accounting for the various features seen around NGC 4216 and discuss what is so special (or not) about this galaxy.

4.1. Real Structures or Artifacts

Disentangling real features from artifacts is essential to the goals of this paper. Although multiple internal reflections in CCDs and stellar halos also produce LSB structures, these instrumental features usually have somewhat regular geometric shapes, like disks, long thin straight lines or grids, while the shapes of the cosmic structures of interest to us are significantly different in appearance: broad filaments, arcs, and irregular plumes. In the case of NGC 4216, a number of the faint structures we noted are (barely) visible on SDSS images (Miskolczi et al. 2011) and more convincingly detected by Martínez-Delgado et al. (2010).

As a reminder, the principal features observed around NGC 4216 and possibly associated with collisional debris are the following.

1. Two long filaments (F1 and F2), with frail evidence that they are physically connected, forming a possible loop in the northwest quadrant of NGC 4216.

2. A less extended very LSB arc-like structure east of NGC 4216 (F3). The dwarf satellite B is found at the intersection of F3 and F1.

3. A relatively high surface brightness filament wrapping around the dwarf galaxy companion VCC 165, likely emanating from a newly discovered disrupted dwarf (D).

4. Several broader and short filaments coming out from main body of NGC 4216 (F5–F7).

4.2. Origin of the Filamentary Structures

Undoubtedly, all the stellar filamentary structures observed in the field of NGC 4216 have been shaped by tidal forces. However, the origin of their stars may be debated. Given the
high frequency of fine structures around the spiral, one may wonder if they were all produced by a single event: either an old merger with a relatively high-mass companion, or ongoing tidal interaction with dwarf galaxies. In these two cases, the dwarfs seen along filament F1 would not be the original progenitors of its stars, but they would instead be tidal dwarf galaxies (TDGs) born in situ from the collisonal debris. In fact, the three aligned dwarfs A, B, and C show similarities with the three also aligned TDG candidates recently discovered along a prominent tidal tail associated with the elliptical galaxy NGC 5557, which was interpreted as an old merger (Duc et al. 2011). However, the latter are gas-rich, contrary to the NGC 4216 dwarfs.

NGC 4216 has at least one relatively massive companion, the edge-on spiral NGC 4222, and two luminous dwarf satellites, VCC 165 and VCC 200 (see Table 1). The latter two galaxies are likely not massive enough to tidally disrupt their host (though the filament F7 pointing toward VCC 200 is intriguing). An ongoing collision between the two spirals would generate tidal tails in the plane of their stellar disks (see review by Duc & Renaud 2013). In fact, all the new features discovered around the galaxy (the stellar protuberances, plumes, and filaments) are located along its minor axis, i.e., perpendicular to its main plane, and not toward the outermost regions of its stellar disk plane, where the isophotes remain regular (see in particular Figure 1).

In H1, Chung et al. (2009) did not find any clear indications of interactions between the two galaxies either, though they noted mild distortions in the kinematics at the edge of the disk in both systems. A major merger in NGC 4216 is thus very unlikely. Furthermore, the outer regions along the major axis of the galaxy, G1 and G2 (see Figure 2), are slightly bluer in \( g - i \) by 0.2 mag than the regions along the intergalactic stellar streams. This likely means that the stellar streams and outer disk of the galaxy do not share the same stellar populations, and thus that the stars in the filaments did not originate from the spiral.

Alternatively, the filamentary structures may result from dwarf galaxies tidally stirred by NGC 4216. In that case, the tails are shaped by both tidal forces and the orbit of the satellite around the host galaxy (Varghese et al. 2011). Inside several of the filaments, stellar bodies with higher surface brightness are found that are good filament progenitor candidates. The most promising one is object A, which shares with filament F1 its orientation and color. Scrutinizing Figure 1, one may see that the filament has an S-shaped structure close to the dwarf, due to the presence of two slightly misaligned tails on each side of the galaxy, possibly the leading and trailing tidal tails. This provides additional evidence that A is the progenitor.

On the other hand, it is hard to determine whether object B belongs to filament F1 or F3, or if it is just a chance superimposition. Its main body is not aligned with any of the filaments while its \( g - i \) color agrees with that of filament F1 (the signal-to-noise ratio of F3 is too low to determine its color). If objects B, as well as C, are indeed associated with F1, their presence along a single filament remains mysterious. It is unlikely that their common progenitor broke into two or even three stellar cores. Alternatively, if A, B, and C were all pre-existing objects, and subsequently tidally disrupted by NGC 4216, one would a priori expect them to be originally on different orbits and therefore to generate filaments with different orientations. Note however that according to cosmological models, satellite accretion occurs along privileged directions. The dwarfs might thus belong to a common cosmological stream. A chance superimposition of B and C is obviously an hypothesis worth exploring. Having spectroscopic data, and in particular information on the radial velocity and chemical abundances, would help to determine the nature of the dwarfs. Alternatively, B and C might be sub-structures born in situ in the tidal tail of A. Such a formation mechanism would differ from the one at the origin of TDGs, as it would not involve a major wet merger. It would rather resemble the one responsible for the formation of the stellar clumps that are commonly found in the tidal streams of Milky Way globular clusters (e.g., Mastrobuono-Battisti et al. 2012). Note that in our own Local Group, the distribution of dwarf satellites inside narrow disks, the so-called disks of satellites (e.g., Pawlowski et al. 2012; Ibata et al. 2013), is also puzzling and no satisfactory solution to account for them has yet been found.

Finally, the origin of the filamentary structures that do not show any obvious progenitor, such as F2 (unless it is connected to F1 and shares the same progenitor), and of the three plume-like filaments (F5–F7) is even less constrained. The progenitors might have been totally disrupted or their remnants might already have been swallowed by the massive spiral. In fact, object D near VCC 165 is likely a case of a dwarf in the process of total disruption. Whether it is disrupted following its interaction with VCC 165 (around which its tidal tail, F4, wraps) or with the more massive but slightly more distant galaxy NGC 4216, or both, is unclear. VCC 165 itself does not seem to be affected by gravitational interactions.

4.3. An Unusual Ongoing Bombardment in a Cluster of Galaxies

The discovery of numerous filamentary structures around NGC 4216, and tidally stretched stellar clumps within them, revealed an impressive number of infalling satellites caught it the act of disruption. When has such a bombardment started and where in the cluster did it occur?

4.3.1. A Sub-structure within the Virgo Cluster?

Could NGC 4216 belong to a sub-structure, like a group that has been accreted by the Virgo Cluster? Within the cluster, NGC 4216 is located in a moderately dense environment: the local projected number density of galaxies is nearly half that of the cluster core. The spiral is the most luminous galaxy within this sub-structure. For each Virgo galaxy more luminous than \( M_B = -18 \), we estimated in the SDSS data set the number of companions within a 100 kpc radius and radial velocities of \( \pm 300 \) km s\(^{-1}\). NGC 4216 turns out to have a significantly higher number of faint companions (\( M_B > -18 \), with spectra available), compared to its fellow galaxies. The probability of an increased number of dwarfs being demolished is thus higher there. The statistics on the ratio of dwarfs to giants is still to be extended to the many faint and ultra-faint dwarfs that are being discovered by the NGVS survey. Low velocity collisions able to generate multiple tidal tails are expected in groups. As a matter of fact, examples of tidal interaction and possibly ram pressure have been observed in several infalling groups of clusters, which are suffering a so-called pre-processing (e.g., Cortese et al. 2006), during which the properties of their galaxies are changed within the group before being affected by the cluster environment.

4.3.2. Timescales for the Satellite Accretion/Destruction

A timescale for the satellite accretion/destruction process may be obtained from the survival time of the debris: whereas around isolated systems, streams may remain visible for several
Gyr, within a cluster, the life expectancy of tidal debris is largely reduced due to dynamical heating and mixing (Rudick et al. 2009). They should evaporate on a timescale shorter than the cluster crossing time, typically 1 Gyr (Trentham & Tully 2002). This suggests that the bombardment has either started within the Virgo Cluster itself or in a pre-processed group that was accreted by the cluster only recently.

The gas content of the NGC 4216 system somehow differs from that of the pre-processed groups so far reported in the literature. The filamentary structures detected in claimed pre-processed groups (e.g., Cortese et al. 2006) are usually gas-rich, host H I regions, and are thus probably star forming. There is no evidence for intergalactic H I gas around NGC 4216, at least in the ALFALFA single-dish survey.

The tails are red, presumably made of old stars. The dwarf satellites around NGC 4216 had their gas stripped long ago, either due to long-lasting interactions with the massive galaxies in the group, or because globally the group members had their gas reservoir stripped before the accretion event. At least in Section 3.1, the H I disk of NGC 4216 seems truncated, which is normally interpreted as a consequence of ram-pressure stripping in the cluster environment: the outer gaseous halo of a spiral galaxy is stripped away when it passes through a high density medium such as the core of a cluster (Vollmer et al. 2001, 2004; Boselli & Gavazzi 2006). This might indicate that the NGC 4216 group already suffered a ram-pressure stripping episode, and therefore that is has already been in the cluster for a long time. The ram pressure needed to strip a spiral down to the observed outer H I radius \( R_{\text{HI}} \) (15 kpc) is roughly \( \Sigma_{\text{HI}} V_{\text{rot}}^2 / R = \rho_{\text{ICM}} V_{\text{gal}}^2 \), where \( \Sigma_{\text{HI}} \) is the H I surface density (3 \( M_{\odot} / \text{pc}^2 \)), \( V_{\text{rot}} \) the rotation velocity (250 km s\(^{-1}\)), and \( V_{\text{gal}} \) the galaxy velocity in the Virgo Cluster (1500 km s\(^{-1}\)). This yields an intracluster medium (ICM) density, \( \rho_{\text{ICM}} \), of \( 3 \times 10^{-4} \) cm\(^{-3}\). According to Schindler et al. (1999), such a density occurs at a cluster radius of about 0.5 Mpc or 1.7. At the present epoch, NGC 4216 is located at a projected distance of 2.5 and 3.6, respectively, from the central cluster galaxies, M86 and M87. Thus, the value of its H I truncation radius suggests a stripping episode that occurred at least 1 Gyr ago, given the galaxy’s velocity, and closer to the cluster core, which would imply that the galaxy has ventured through that environment in the past. The bombardment of NGC 4216 and the multiple dwarf destruction must then have occurred later on.

Alternatively, the H I truncation of NGC 4216 might be possible without invoking the Virgo ICM, if the group were sufficiently massive and X-ray luminous (Sengupta et al. 2007; Kern et al. 2008). There is however no evidence for extended X-ray emission at the location of the galaxy to support the hypothesis of an in situ ram-pressure event (see Figure 7 in Chung et al. 2009). Finally, one should note that one of the main characteristics of the gas property of NGC 4216, more striking than the disk truncation, is its overall low H I surface density for a spiral galaxy of its size. Such a global depletion of H I might in fact be due to the effect of turbulent viscous stripping (Nulsen 1982; Cayatte et al. 1994; Chung et al. 2009) rather than ram-pressure stripping.

Furthermore, taking into account the fact that the companion galaxy, NGC 4222, has a regular H I distribution, it is still difficult to firmly conclude that the group of NGC 4216 did experience a ram-pressure event during a past journey through or near the cluster core.

4.3.3. How Unique is NGC 4216?

How special is NGC 4216 within the Virgo Cluster? As part of the NGVS project, we have identified in a systematic way LSB stellar tails, and cases of tidally disrupted dwarfs. Our preliminary analysis over most of the Virgo Cluster area indicates that there are only a rather small number of them, especially around spiral galaxies (P. A. Duc et al. 2013, in preparation). This may be an additional argument in agreement with a recent accretion of NGC 4216 as part of a group.

On the other hand, even in the field and in groups, a bombardment like the one suffered by NGC 4216 seems pretty rare. None of the spirals mapped by Martínez-Delgado et al. (2010) have a similar number of filaments and disrupted dwarfs around them. In some systems, what appears to be multiple loops may in fact be the wrapping of a single tidal stream around its host (e.g., Martínez-Delgado et al. 2009). In the case of NGC 4216, several independent filaments are observed; they emanate from at least two, likely four, different disrupted dwarfs. The ongoing deep imaging survey with MegaCam of Atlas3D field galaxies (Duc et al. 2011), which has a similar depth and sensitivity to LSB structures as the NGVS, has so far also failed to detect the same wealth of debris of minor mergers observed around NGC 4216. On the other hand, multiple stellar streams and dwarf satellite progenitors have been identified in the halo of our own Milky Way (Ibata et al. 2001; Yanny et al. 2003; Grillmair 2006). They are however of much lower surface brightness. Were the NGVS able to reach the surface brightness limit achievable with resolved stellar populations—32 instead of 29 mag arcsec\(^{-2}\)—then the number of filaments and satellites is expected to strongly increase according to numerical simulations (Bullock & Johnston 2005; L. Michel-Dansac et al. 2013, in preparation).

5. CONCLUSIONS

We have presented a study of the properties and origins of a complex series of interlaced narrow filamentary stellar structures, loops, and plumes located in the vicinity of the edge-on Virgo Cluster spiral galaxy NGC 4216. They were detected on multi-band extremely deep optical NGVS images. Some streams had already been identified in previous surveys, e.g., Martínez-Delgado et al. (2010). Several others, with g-band surface brightness levels fainter than 28.5 mag arcsec\(^{-2}\) are reported here for the first time.

Whereas the tidal origin of the filamentary structures seems rather obvious, determining the progenitors of their stars is less straightforward. The high resolution of the MegaCam camera, besides its high sensitivity to LSB features, allowed us to identify progenitor candidates and to further explore the complexity of the system. This is illustrated by the detection of satellites of satellites: a filament was found wrapping itself around the luminous dwarf VCC 165, which itself is probably orbiting around NGC 4216. The alignment of three dwarfs

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\(^{17}\) Considering that some large-scale gas features of low column density such as the Virgo H I plume discovered by the Westerbork Synthesis Radio Telescope (Oosterloo & van Gorkom 2005) have been missed in single-dish surveys, deeper imaging studies with interferometers which will not resolve out diffuse gas will help to ensure the absence of intergalactic gas.

\(^{18}\) The true distance and location of NGC 4216 within the Virgo Cluster is not known. An estimate of the distance based on surface brightness fluctuations is only available for one possible group member, VCC 200. Blakeslee et al. (2009) determined a distance of 18.2 ± 0.6 Mpc for this galaxy. The group thus may be located further from M87, at ~2 Mpc (calculated three-dimensional distance using radial and projected distances 1.7 and 1.2 Mpc, respectively). This yields a travel time from the center of Virgo Cluster to the current position of nearly 2 Gyr.
along an apparently single stream is also intriguing. Projection
effects might be an explanation unless some of them are
second-generation objects formed in situ in tidal debris, or
if all the dwarfs were accreted from the same cosmological
filament.

The dominant spiral itself does not show any strong evidence
of having experienced a recent merger or being currently
involved in a tidal interaction with a massive companion.
The stellar streams most likely result from the disruption of
dwarf satellites, some of which are still visible but look highly
interrupted on the NGVS images.

While dwarf galaxy accretion, with an associated high rate
of satellite destruction and the formation of stellar streams,
is a priori expected for massive galaxies—cosmological semi-
analytical models and simulations predict that they grow at low
redshift through minor mergers (Naab et al. 2009; Khochfar
et al. 2011; McLure et al. 2013)—their presence in a cluster
environment is rather surprising. A possible explanation is that
NGC 4216 is the central galaxy of a group that has recently
fallen into the Virgo Cluster; and that the merging activity seen
in its surroundings might be considered as evidence for pre-
fall. The stellar streams most likely result from the disruption of
numerous satellites, joined the Virgo Cluster.

We have carried out a preliminary comparison of the fine
structure index of NGC 4216 with that determined in other spiral
galaxies in the Virgo Cluster, but also around massive galaxies
in the field and in groups. NGC 4216 seems to have a particularly
high number of streams typical of minor mergers, and associated
dwarfs caught in the act of being disrupted. We intend to confirm
this as part of other ongoing deep surveys with the Megacam
camera on the CFHT. The significance and implications of its
results should also be probed using numerical simulations of
galaxy evolution which may tell whether NGC 4216 has indeed
had an unusually rich recent accretion history, if on the contrary
its fellow members have had a much less important minor merger
activity than predicted, or whether our knowledge of stellar
streams and its associated timescales should be revisited.

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