The Widefield Arecibo Virgo Extragalactic Survey. I. New Structures in the ALFALFA Virgo 7 Complex and an Extended Tail on NGC 4522

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Abstract

We are carrying out a sensitive blind survey for neutral hydrogen (H I) in the Virgo cluster and report here on the first $5^\circ \times 1^\circ$ area covered, which includes two optically dark gas features: the five-cloud ALFALFA Virgo 7 complex and the stripped tail of NGC 4522. We discover a sixth cloud and low-velocity gas that extends the velocity range of the complex to over 450 km s$^{-1}$, find that around half of the total H I flux comes from extended emission rather than compact clouds, and see around 150% more gas, raising the total HI mass from 5.1 $\times 10^8 M_\odot$ to 1.3 $\times 10^9 M_\odot$. This makes the identification of NGC 4445 and NGC 4424 by Kent et al. as possible progenitors of the complex less likely, as it would require an unusually high fraction of the gas removed to have been preserved in the complex. We also identify a new component to the gas tail of NGC 4522 extending to ~200 km s$^{-1}$ below the velocity range of the gas in the galaxy, pointing toward the eastern end of the complex. We consider the possibility that NGC 4522 may be the parent galaxy of the complex, but the large velocity separation (~1800 km s$^{-1}$) leads us to rule this out. We conclude that, in the absence of any better candidate, NGC 4445 remains the most likely parent galaxy, although this requires it to have been particularly gas-rich prior to the event that removed its gas into the complex.

Key words: galaxies: clusters: individual (Virgo) – galaxies: individual (NGC 4522) – radio lines: galaxies

1. Introduction

Virgo has long been a fertile ground for searches for neutral hydrogen (H I) gas unassociated with optical counterparts. These include well-known examples such as H I 1225+01 (Giovanelli & Haynes 1989; Giovanelli et al. 1991; Chengalur et al. 1995) and VIRGOH 21 (Davies et al. 2004; Minchin et al. 2005, 2007; Haynes et al. 2007), which are extended sources with $M_{HI} \sim 10^8$–$10^9 M_\odot$, as well as many other clouds revealed in recent years, primarily by the Arecibo Legacy Fast Arecibo L-band Feed Array (ALFALFA) survey (Kent et al. 2007) and the Arecibo Galaxy Environment Survey (AGES; Taylor et al. 2012). Such dark features may be debris from tidal encounters between galaxies, or they may have their origin in the removal of gas from galaxies via ram pressure stripping by the intra-cluster medium (ICM).

With this in mind, we have begun the Widefield Arecibo Virgo Extragalactic Survey (WAVES). This is an extension of AGES in the Virgo Cluster, with the specific intention of revealing the low column-density neutral hydrogen (H I) content of the cluster. WAVES is currently covering the R.A. range of $12^h09^m00^s$–$12^h49^m00^s$ and the decl. range of $09^\circ00^\prime$–$11^\circ06^\prime00^\prime$, filling in the gap between the AGES VC1 (Taylor et al. 2012) and VC2 (Taylor et al. 2013) fields to the same sensitivity and spectral resolution as AGES.

The first quadrant of the survey, covering a 5 square degree area over R.A. $12^h29^m00^s$–$12^h49^m00^s$ and decl. $09^\circ00^\prime$–$10^\circ00^\prime00^\prime$, was completed in 2018 March. This takes in the area of the ALFALFA Virgo 7 complex, a dark H I cloud complex discovered by the ALFALFA survey (source 7 in Kent et al. 2007), and identified as consisting of five clouds lying between 400 and 760 km s$^{-1}$ (see also our Figure 2). Very Large Array (VLA) observations (Kent et al. 2009) confirmed two of the clouds (C1 (7c) and C2 (7d)) but did not detect clouds C4 (7b) or C5 (7e) due to their distances from the pointing center. Cloud C3 (7a) lies outside of the area mapped by the VLA. Sorgho et al. (2017) also covered this region with a combined Westerbork Synthesis Radio Telescope (WSRT) and KAT-7 map; they detected cloud C1 but not cloud C4, which should have been detectable based on its single-dish H I mass if it were a point source. The ALFALFA map of Kent et al. (2009, their Figure 2) shows two of the five clouds in the complex (C1 and C4) to be connected, but the other three clouds are separated at their sensitivity level. They find a total mass for the complex of $5.1 \times 10^8 M_\odot$ at an assumed distance for the Virgo cluster of 16.7 Mpc, equivalent to a total flux of 7.8 Jy km s$^{-1}$.

Kent et al. (2009) found that a possible optical counterpart near the C2 cloud, VCC 1357, had a large separation from the VLA position and was thus unlikely to be associated with the complex.

The ALFALFA Virgo 7 complex is thus a unique structure in the Virgo cluster. Only one other H I feature is known that is detached from its parent galaxy—the cloud associated with VCC 1249 (Arrigoni Battaia et al. 2012). However, in that case the cloud is only at a 14 kpc projected distance from its parent, whereas the nearest plausible parent for the complex (NGC 4445) is separated by ~180 kpc in projection from its center. The complex is also among the most massive of the streams known in Virgo and has a highly complex internal structure. No other feature in Virgo shows this combination of features. We describe our observations of the complex in Section 3.
This first quadrant also takes in the galaxy NGC 4522, a classic example of ram pressure stripping in the Virgo cluster (Kenney & Koopmann 1999). This has a well-known H I tail, observed by Kenney et al. (2004) and Chung et al. (2007) and simulated by Vollmer et al. (2006). Like the ALFALFA Virgo 7 complex, the tail of NGC 4522 is an example of optically dark H I gas in Virgo although, unlike the complex, it remains connected to its parent galaxy and the mechanism by which it has been created is much clearer. We describe our observations of NGC 4522 in Section 4.

All velocities in this paper are radial velocities in the barycentric frame and the optical ($cz$) convention.

2. Observations

Observations on this field were made between 2017 January and 2018 March using the Arecibo L-band Feed Array (ALFA). WAVES uses the same scan pattern and data reduction pipeline as AGES (detailed in Auld et al. 2006). As around half of the data were taken prior to Hurricane Maria (2017 September 20), which caused changes to the gain of the Arecibo telescope, and half afterwards, separate cubes were initially made from each half of the data set and their respective flux calibrations were compared using the fluxes of strong H I sources within the cube. An adjustment of around 8% was then made to the post-Maria calibration and the post-Maria data sources within the cube. An adjustment of around 8% was then made to the post-Maria calibration and the post-Maria data were re-reduced with the new calibration before the final data cube was made.

2.1. Verification of the Flux Scale

We check our calibration by comparing our total H I fluxes to those seen by ALFALFA. There are 33 sources in the ALFALFA catalog of Kent et al. (2008) within the WAVES quadrant boundary. After removal of high velocity clouds (HVCs), the extended clouds from the complex, lower quality (code 2) sources, and sources noted to have issues with their parameter fitting, we are left with 17 sources. Two of these lie too close to the edge of our cube to be well parameterized in WAVES, giving 15 good comparison sources. In Figure 1 we compare our fluxes for these sources to the ALFALFA fluxes from Kent et al. (2008) and the rescaled ALFALFA fluxes from Haynes et al. (2018), which are, on average, 8% higher. We find the weighted mean of the ratio of the WAVES flux to the Kent et al. (2008) flux is 1.07 ± 0.04 and for the Haynes et al. (2018) flux is 0.96 ± 0.04. Our flux scale thus appears to be slightly higher than the initial ALFALFA flux scale, but is consistent with their corrected flux scale.

3. The ALFALFA Virgo 7 Complex

Around the velocity of the ALFALFA Virgo 7 complex, our observations reach an average noise level of 0.9 mJy beam$^{-1}$ at a Hanning-smoothed velocity resolution of 10 km s$^{-1}$, around three times deeper than the ALFALFA observations.

Figure 2 shows the moment 0 map of the complex over 440–620 km s$^{-1}$ with the outer contour at $3\sigma$ (0.18 Jy km s$^{-1}$, $5 \times 10^{18}$ cm$^{-2}$), the second contour at $5\sigma$ (0.30 Jy km s$^{-1}$, $8 \times 10^{18}$ cm$^{-2}$), and other contours at increasing steps to bring out the peaks of the clouds. The five clouds identified in the complex by Kent et al. (2007, 2009) can be clearly seen, but we also see a sixth cloud (which we label as C6 for consistency with the nomenclature of Kent et al. 2009) between C4 and C2.

Figure 3 shows channel maps averaged over 55 km s$^{-1}$ and color coded by velocity, over the range 280–780 km s$^{-1}$. It is apparent that, unlike in the map of Kent et al. (2009), at the WAVES sensitivity level the whole complex is joined up by H I bridges. We also see gas down to 280, 120 km s$^{-1}$ below the lower limit of the gas seen by Kent et al. (2009); this is shown by violet and purple contours in Figure 2. The new cloud C6 is visible in the cyan and green contours, and partly in the yellow contours.

Cloud C4 can be clearly seen to consist of two overlapping components, with a shift in the center of around 2:5 between the cyan and green contours and the orange and red contours. The higher velocity component has a position (fitted over 640–760 km s$^{-1}$) of $12^h30^m24^s0$, 09°36′50″ while the lower velocity component has a position (fitted over 460 to 580 km s$^{-1}$) of $12^h30^m17^s7$, 09°34′40″. Spectra of the two components (summed over a 5′ × 5′ box) are shown in Figure 4.

Kent et al. (2009) describe cloud C3 as unresolved with the ALFA beam. However, we see the cloud as being clearly extended along an axis pointing toward C1, with the center shifting further along this axis (away from C1) at higher velocities. This can be seen in Figure 5. A bridge between cloud C3 and the main complex can be seen in the blue and cyan contours and in the gray scale on this figure, which covers the same velocity range. The bridge connects to an extension seen at low signal-to-noise (S/N) to the west side of C4 in the Kent et al. (2009) map, which is now seen to be real (conversely, the extension to the northeast side of C4, seen at a very similar flux level in the Kent et al. 2009 map, is not seen in our data). However, in velocity space the connection looks to
be to C1 (which would be consistent with the alignment of the axis of cloud C3) rather than to C4.

Clouds C2 and C5 contain lower velocity gas than that seen by Kent et al. (2009), which bridges between the two clouds; this is marginally visible (at around 2\(\sigma\)) in the Kent et al. (2009) spectrum of C2 but is clearly detected here. This is shown in Figure 6. It can be seen that there is detected gas at the positions of C5 and C2, stretching about half way to the position of C6 and with the peak in the 280–340 km s\(^{-1}\) map about half way between C5 and C2. There is also gas in the main complex, with a peak between the positions of C1 and C4, stretching to the root of the bridge to C3. The gas in this velocity range does not contribute greatly to the total HI content of the complex, with \(F_{\text{HI}} = 0.34\) Jy km s\(^{-1}\) (after sidelobe correction, see below) for an H\(1\) mass of \(2.3 \times 10^7 M_\odot\), i.e., less than 2\% of the total H\(1\) mass of the complex. Nevertheless, it provides important information on the connections between the clouds.

The bay between C2 and C1, south of the new C6 cloud, is not completely filled in at any of the velocity slices, even though almost all of its area is covered at some velocity or other (see Figures 2 and 3). We fit a position for the C6 cloud (using a 5\(^{\prime}\) \(\times\) 5\(^{\prime}\) box) of 12\(^{\text{h}}\)30\(^{\text{m}}\)46\(^{\text{s}}\), 09\(^{\text{h}}\)34\(^{\text{m}}\)04\(^{\text{s}}\). The flux in the single-pixel spectrum at this position is \(0.78 \pm 0.12\) Jy km s\(^{-1}\), with a peak of only 6 mJy, making it less than 3\(\sigma\) in the Kent et al. (2007, 2009) data, while the beam-corrected flux within the 5\(^{\prime}\) \(\times\) 5\(^{\prime}\) box is \(0.97 \pm 0.13\) Jy km s\(^{-1}\). The total flux measured off the moment 0 map within a 7\(^{\prime}\) \(\times\) 8\(^{\prime}\) box enclosing C6 is \(1.62 \pm 0.12\) Jy km s\(^{-1}\).

3.1. Total H\(1\) Content of the Complex

We measure the H\(1\) flux of the complex in two ways: by measuring the total flux in a moment 0 map summed spectrally across the 260–790 km s\(^{-1}\) velocity range in a 37\(^{\prime}\) \(\times\) 35\(^{\prime}\) region centered on 12h30m41s, 09\(^{\text{h}}\)30\(^{\text{m}}\)38\(^{\text{s}}\) (fully enclosing points above 3\(\sigma\) on the moment 0 map) and by measuring the total flux over the same velocity range in a spectrum summed spatially across the same region (these are shown in Figure 7). These are corrected using a circular Gaussian beam of HPBW 3/4. The moment 0 map gives a total flux of 26.6 \(\pm\) 1.3 Jy km s\(^{-1}\) and the spectrum gives a total flux of 28.0 \(\pm\) 1.7 Jy km s\(^{-1}\). While these are not significantly different, they are different enough that using a polygonal map to better fit the shape of the complex is unlikely to bring a major improvement in S/N while potentially missing some diffuse gas. Combining the measurements from the two methods gives a value of 27.3 \(\pm\) 2.2 Jy km s\(^{-1}\).

This total flux measurement needs to be adjusted for the sidelobes, which are not included in the Gaussian primary beam correction, and which contain significant flux scattered out of the main beam. As the first minimum occurs at \(\sim 3^{\prime}\) from the beam center and the peak of the first sidelobe is at \(\sim 5^{\prime}\), for a measurement box size larger than 5\(^{\prime}\) \(\times\) 5\(^{\prime}\) at least part of the first sidelobe will fall within the box and will thus lead to an overestimate of the flux if this is not corrected for (a sidelobe correction is not necessary for normal point-source measurements in AGES as these are made within a 5\(^{\prime}\) \(\times\) 5\(^{\prime}\) box, falling entirely within the \(\sim\)3/7 radius of the first minimum and thus not including any sidelobe flux). A box of size 15\(^{\prime}\) \(\times\) 15\(^{\prime}\)
or greater should fully enclose the first sidelobe, thus our map (which is substantially larger than this) will contain both main beam flux and flux from the sidelobes, both of which will contribute to our measured flux. Heiles et al. (2001) found the ratio of the first sidelobe and main beam efficiencies to be \( \eta_{\text{FS}} / \eta_{\text{MB}} = 0.33 \) for the L-band wide feed, while Heiles (2004) found values for the ALFA beams of \( \eta_{\text{FS}} / \eta_{\text{MB}} = 0.16 \) for the central beam and varying from 0.30 to 0.38 for the outer beams. The average across all ALFA beams is \( \eta_{\text{FS}} / \eta_{\text{MB}} = 0.31 \) and the median is 0.33. We adopt a value of \( \eta_{\text{FS}} / \eta_{\text{MB}} = 0.33 \) and correct our measured flux by a factor of \( 1 + \eta_{\text{FS}} / \eta_{\text{MB}} \), giving \( 20.5 \pm 1.7 \text{ Jy km s}^{-1} \). This assumes no significant contribution from other sidelobes: as \( (\eta_{\text{MB}} + \eta_{\text{FS}}) = 0.75 \), sidelobes beyond the first contain around 25% of the total flux, but the majority of this will be scattered well outside our map; we therefore follow Peek et al. (2011) in not attempting a correction for the more distant sidelobes.

We therefore measure a total H\( \text{I} \) mass of \( 1.3 \pm 0.1 \times 10^9 M_\odot \), assuming the same distance of 16.7 Mpc used by Kent et al. (2009). This is considerably higher than their total H\( \text{I} \) mass measurement of \( 5.1 \times 10^9 M_\odot \). However, their total flux is simply the sum of the flux found in each cloud, to which we have added substantial extended emission and emission from smaller clouds that could explain the discrepancy. To check this, we compare the measurements from single-point spectra at the locations Kent et al. (2009) and identify as the cloud centers. For consistency, the errors for Kent et al. (2009) were recalculated using the formulae of Koribalski et al. (2004) and the quoted S/N.

We find that our measurements of the individual clouds are consistent with Kent et al. (2007, 2009). There are no significant differences in fluxes on individual clouds between the WAVES single-point spectra and the Kent et al. (2009) measurements, and summed across the five clouds identified by Kent et al. (2009) we see less emission than they do, although not significantly (7.20 \( \pm \) 0.30 versus 7.83 \( \pm \) 0.92 Jy km s\(^{-1} \); errors following Koribalski et al. 2004). Thus the extra flux seen in our map would appear to be from extended emission and newly identified clouds not included in the total by Kent et al. (2009). The only significant difference between our measurements and Kent et al. (2009) is on the central velocity and velocity width of cloud C3. This inconsistency can be traced to a narrow secondary peak near 600 km s\(^{-1} \) that is above 50% of the flux of the primary peak in the Kent et al. spectrum, thus increasing their 50% velocity width and shifting their velocity center, but which falls below 50% of the peak of the primary in the corresponding single-point WAVES spectrum (the peak in question can be seen in our spatially integrated spectrum of C3 in Figure 8, where it is again above 50%).

3.2. H\( \text{I} \) Parameters of Individual Clouds

Measuring over a 5\( \prime \) \times 5\( \prime \) box allows us to fit positions for the clouds in addition to measuring their parameters (Table 1). In addition to the five clouds found by Kent et al. (2007, 2009), we also fit for cloud C6 and the new low-velocity components of clouds C2 and C5, here labeled C2b and C5b, which are separated kinematically from the clouds found by Kent et al. (2009). Although cloud C4 has two distinct center positions these are not clearly separated kinematically; thus we only make a single measurement of the flux, velocity width, etc., for that cloud. The spectra associated with these measurements are given in Figure 8.

The gas clouds identified in Table 1 contribute a total flux of 11.2 \( \pm \) 0.4 Jy km s\(^{-1} \), compared with our measurement of 20.5 \( \pm \) 1.7 Jy km s\(^{-1} \) for the complex as a whole. Diffuse gas in between the compact clouds would thus appear to be
responsible for at least 45% ± 4% of the total gas in the complex, with the strong possibility that more exist below our detection threshold. Unlike in the single-point spectra discussed above, the fluxes in these spatially extended spectra are higher than those found by Kent et al. (2009) for the same clouds, indicating the likely presence of extended flux around these sources.

4. NGC 4522

NGC 4522 is a classic example (see Figure 9) of a galaxy that is undergoing ram pressure stripping, giving rise to an optically dark H I tail of gas removed from the galaxy. VLA H I observations by Kenney et al. (2004) and Chung et al. (2007) show a tail of around 40″ in length beyond the plane of the galaxy; Kenney et al. (2004) further derive an H I deficiency of 0.6, indicating that around three quarters of the original gas content has been lost from this galaxy. Vollmer et al. (2006) successfully simulate the extra-planar H I and the H I deficiency by assuming that the galaxy is traveling at a high speed (∼3500 km s⁻¹) relative to the ICM, either because it is not bound to the cluster or because the ICM is itself moving with respect to the cluster due to the infall of the M49 group. In their simulations, the galaxy has an initial gas mass of 1.3 × 10⁸ M☉, of which 9 × 10⁸ M☉ is lost.

To this, our new observations add the discovery of a high-velocity (relative to the galaxy) extension of the gas tail of NGC 4522. This stretches about 200 km s⁻¹ below the velocity of the H I seen in the galaxy, to a recessional velocity of 2000 km s⁻¹, and has a slight inclination seen in a velocity–R. A. map (Figure 10), shifting around 25 s in R.A. (6′ = 30 kpc at a distance of 16.7 Mpc) west along its length to 13:33:15.
The Vollmer et al. (2006) simulations reproduced the blueshift of the H I velocities in the tail relative to the galaxy seen in the VLA observations of Kenney et al. (2004), but not the velocity width seen there of 150 km s$^{-1}$ (full width at zero intensity). Our addition of an extra 200 km s$^{-1}$ to this is thus well out of the range of gas dynamics reproduced by the simulations. The direction of the tail we observe is consistent with the angle of −15 deg (north of west) assumed by Vollmer et al. (2006) based on Hubble Space Telescope observations.

The extension of the tail can be seen in the spectrum of NGC 4522 as a faint wing on the low-velocity side of the main peak (Figure 10). From measurements on the spectrum, summed over a 13′ × 7′ box centered on 12h33m30s,09′ 12′00s, the wing has an H I flux of 0.9 ± 0.2 Jy km s$^{-1}$ within a velocity range from the minimum between the galaxy and the tail at 2180 km s$^{-1}$ to when it falls to zero intensity at 1945 km s$^{-1}$. This gives an H I mass (16.7 Mpc) of 5.9 ± 1.3 × 10$^7$ M$_\odot$. By comparison we measure (on the same spectrum) a flux of 7.9 ± 0.5 Jy km s$^{-1}$ for the galaxy between the minimum at 2180 km s$^{-1}$ and when it falls to zero intensity at 2490 km s$^{-1}$ equivalent to 5.2 × 10$^8$ M$_\odot$ (due to the size of the box, this will include a small contribution from the sidelobes). Measurements assuming a point source at the position of the H I peak of the galaxy give a flux of 6.4 ± 0.3 Jy km s$^{-1}$, equivalent to 4.2 × 10$^8$ M$_\odot$. These are both consistent with the 7 ± 1 Jy km s$^{-1}$ measured in a single Arecibo pointing by Helou et al. (1984), and bracket the 7.17 ± 0.10 Jy km s$^{-1}$ measured by ALFALFA (Haynes et al. 2018).

5. Discussion—Possible Origins of the ALFALFA Virgo 7 Complex

Kent et al. (2009) propose that a possible scenario for the origin of the complex is stripping from a galaxy, with the nearby galaxies NGC 4445 and NGC 4424 (both at similar redshifts to the complex) being identified as possible candidates for the parent galaxy. Our results above, showing an alignment both spatially and in velocity space between the complex and the tail of NGC 4522, mean that we must also consider the possibility that this galaxy is associated with the complex. In Figure 11 we show the region around the complex, with the nearby galaxies labeled and color coded by redshift, and with H I contours shown for those detected in WAVES.

An approximate separation/dispersion timescale for the complex can be calculated from the velocity differences between the clouds, ΔV, and their projected separation, r, i.e., τ ∼ r/ΔV, assuming a common starting point. It can be seen from Table 2 that a timescale of around 1 Gyr is consistent with the current dispersion of the clumps in the cloud. It can also be seen that if, alternatively, the complex is a bound system (which seems highly unlikely) it would have a dynamical mass of approximately 10$^{11}$–10$^{12}$ M$_\odot$.

The ALFALFA Virgo 7 complex is similar in some ways to the cloud H1 1225+01 in the Virgo southern extension (Giovanelli & Haynes 1989; Giovanelli et al. 1991). At their assumed distance of 20 Mpc, H1 1225+01 has a total mass of 4.9 × 10$^9$ M$_\odot$ with the two clumps to the northeast and southwest of the cloud having masses of 2.4 × 10$^9$ M$_\odot$ and 1.3 × 10$^9$ M$_\odot$, respectively (Giovanelli et al. 1991). Approximately a third of the emission is from diffuse gas rather than from the two clumps. This combination of multiple H I clouds and diffuse emission is reminiscent of the complex here, but there are important differences. The more massive northeast...
Figure 8. Spectra of the clouds used for the measurements in Table 2. Left to right, top row: C1, C2; second row: C2b, C3; third row: C4, C5; bottom row: C5b, C6. For all spectra, dotted lines indicate the velocity range used to derive the parameters given in Table 1. The region used for the baseline fit is indicated by the extent of the spectra; dashed lines indicate velocity ranges excluded from the fit due to possible contamination from the complex or Galactic gas.
clump of H I 1225+01 hosts a low surface brightness dwarf irregular galaxy, J1227+0136 (Djorgovski 1990; Impey et al. 1990; McMahon et al. 1990), although no counterpart has been found to the southwest clump despite repeated searches down to 27–28 mag arcsec$^{-2}$ (Impey et al. 1990; Salzer et al. 1991; Turner & MacFadyen 1997; Matsuoka et al. 2012). Chengalur et al. (1995) suggested that the southwest clump could be an edge-on disk; it has also been suggested (Turner & MacFadyen 1997) that it could be a tidal tail from the northeast clump although this has not been the subject of detailed modeling.

### 5.1. NGC 4445 and NGC 4424

These two galaxies were suggested by Kent et al. (2009) as possible parent galaxies, but the discovery of much more neutral hydrogen in the complex affects the likelihood of this. They have estimated original H I masses based on their optical diameters and morphological types (Solanes et al. 1996) of $1.2_{-0.6}^{+0.9} 	imes 10^8 M_\odot$ and $1.7_{-0.8}^{+1.4} 	imes 10^9 M_\odot$, respectively, at our adopted distance for the complex of 16.7 Mpc. We measure an H I mass for the complex of $1.3_{-0.1}^{+0.1} 	imes 10^8 M_\odot$. Sorgo et al. (2017), using a combined WSRT and KAT-7 map, measure current H I masses for these galaxies, corrected to our adopted distance, of $0.3_{-0.1}^{+0.1} 	imes 10^8 M_\odot$ and $2.4_{-0.5}^{+0.5} 	imes 10^9 M_\odot$. This means they have lost $1.2_{-0.6}^{+0.9} 	imes 10^8 M_\odot$ and $1.5_{-0.8}^{+1.4} 	imes 10^9 M_\odot$, respectively. The gas detected in the complex would thus account for 110% of the expected gas lost from NGC 4445 or 85% of the expected gas lost from NGC 4424. Even taking the upper ends of these distributions, the gas detected in the complex would account for over 60% of the gas lost from NGC 4445 and over 45% of the gas lost from NGC 4424. By comparison, most previously known H I streams in Virgo account for 20% or less of the expected (upper end) mass lost from their parent galaxies (R. Taylor et al. 2019, in preparation), while the new streams identified in that paper generally contain less than 10% of the mass lost from their parents. The ALFALFA Virgo 7 complex would thus, if it originated in either of these galaxies, contain a uniquely high fraction of the missing gas from its progenitor galaxy for any dark feature.

Of the two, the more obvious candidate is NGC 4445: it has lost virtually all of its original gas mass and it is close by and at a similar velocity to the complex. As the ram pressure necessary to account for the deficiency of NGC 4445 is higher than the pressure estimated at its present location, it is likely to have had its stripping in the past (Koppen et al. 2018). However, as mentioned above, even if it were unusually gas-rich the H I mass we measure in the complex would account for over 60% of the gas lost from this galaxy. Evaporation for a free-floating cloud is expected to be at a rate of 1–10 $M_\odot$ per year, or around $10^9 - 10^{10} M_\odot$ over the approximately 1 Gyr timescale of the cloud (R. Taylor et al. 2019, in preparation), so this accounts for the rest of the gas lost. If NGC 4445 is the parent galaxy of the complex, this implies that we have now discovered virtually all of the gas to be found and that it has been removed from the galaxy remarkably efficiently, with little gas dispersed to low column densities. NGC 4445 has a short tail pointing away from the complex (Sorbo et al. 2017) and is not well aligned with the complex, although if the stripping occurred near a pericentric passage and both objects have moved and separated since then this is not a strong objection.

NGC 4424 lies close to NGC 4445 both spatially and in velocity. The amount of gas lost from this galaxy is more consistent with the gas seen in the complex, but it is known to be currently losing gas via ram pressure stripping, with a long H I tail to the southeast (Chung et al. 2007; Sorbo et al. 2017). This creates not only an alignment problem—the tail points nowhere near the complex—but also the problem that creating the complex as a structure separate from the current tail would require two discrete stripping episodes. It is hard to envision a scenario in which this could occur, without requiring significant, unexpected substructure in the ICM of Virgo.

### 5.2. NGC 4522

Could there be a connection between the ALFALFA Virgo 7 complex and NGC 4522? It can be seen from Figures 11 and 12 that there is an intriguing alignment on the sky between NGC 4522, VCC 1437, and the complex, similar to that expected if the complex were deposited as a stream by NGC 4522. Figure 13 shows that there is also an alignment in velocity space between the current tail and the eastern end of the complex (and VCC 1437), making it very tempting to interpret these as being connected. Based on NGC 4522’s optical radius (Sloan Digital Sky Survey, isophotal) of 120 and its Sc morphology it is expected to have had (following Solanes et al. 1996) an initial mass of $2.5_{-0.9}^{+1.3} 	imes 10^9 M_\odot$, while our measurement of 7.9 ± 0.5 Jy km s$^{-1}$ gives an H I mass (at 16.7 Mpc) of $5.2_{-0.3}^{+0.3} 	imes 10^9 M_\odot$, for a loss of $1.5_{-0.8}^{+1.4} 	imes 10^9 M_\odot$, which is consistent with the H I mass needed to form the complex and gives a deficiency of 0.7 ± 0.2.

However, NGC 4522’s recessional velocity of 2330 km s$^{-1}$, over 1800 km s$^{-1}$ higher than the complex, throws up two challenges: first, the extreme velocity difference between the complex and the galaxy makes any connection between the two

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**Table 1**

Measurements of the Clouds in a 5' × 5' Box

| ID  | R.A. (J2000) | Decl. (J2000) | $V_{LSR}$ (km s$^{-1}$) | $W_{LSR}$ (km s$^{-1}$) | $W_{beam}$ (km s$^{-1}$) | $F_{HI}$ (Jy km s$^{-1}$) | $M_{HI}$ (10$^5$ $M_\odot$) | $S_{peak}$ (mJy) | Peak SNR |
|-----|--------------|--------------|-------------------------|-------------------------|------------------------|-----------------------------|-----------------------------|-----------------|---------|
| C1  | 12:30:24.6   | 09:27:59     | 496 ± 2                 | 70 ± 5                  | 113 ± 7                | 3.06 ± 0.22                | 2.01 ± 0.14                 | 35 ± 6          | 12      |
| C2  | 12:31:19.2   | 09:28:40     | 607 ± 3                 | 57 ± 7                  | 108 ± 10               | 0.94 ± 0.10                | 0.62 ± 0.06                 | 14 ± 18         | 8.0     |
| C2b | 12:31:19.9   | 09:28:59     | 386 ± 7                 | 127 ± 14                | 192 ± 21               | 0.57 ± 0.09                | 0.37 ± 0.06                 | 6 ± 8           |         |
| C3  | 12:29:42.2   | 09:42:39     | 538 ± 2                 | 121 ± 4                 | 148 ± 7                | 1.40 ± 0.12                | 0.91 ± 0.08                 | 15 ± 23         |         |
| C4  | 12:30:19.9   | 09:35:47     | 566 ± 4                 | 172 ± 8                 | 278 ± 12               | 2.73 ± 0.16                | 1.79 ± 0.11                 | 16 ± 29         |         |
| C5  | 12:31:25.8   | 09:18:49     | 486 ± 4                 | 63 ± 8                  | 144 ± 11               | 1.27 ± 0.11                | 0.83 ± 0.07                 | 16 ± 27         |         |
| C5b | 12:31:28.7   | 09:18:29     | 307 ± 8                 | 57 ± 15                 | 107 ± 23               | 0.28 ± 0.07                | 0.18 ± 0.05                 | 4 ± 6.7         |         |
| C6  | 12:30:47.3   | 09:34:04     | 538 ± 5                 | 115 ± 11                | 164 ± 16               | 0.97 ± 0.13                | 0.64 ± 0.09                 | 9 ± 11          |         |

**Note.** Errors calculated using the formulae of Koribalski et al. (2004).
appear unlikely (Kent et al. 2009 do not consider NGC 4522 except to note that it is close in projection but in a different velocity regime). Second, the distance from C3 to NGC 4522 is 68', while the distance from C5 is 35'. If the complex had been laid down as NGC 4522 moved through the cluster, we might expect the velocity C5 to lie about half way between that of C3 and NGC 4522, i.e., about 900 km s\(^{-1}\) higher. But C5 actually lies at a velocity 52 ± 4 km s\(^{-1}\) lower than that of C3.

Although NGC 4522 lies at a significantly different velocity, it has already been posited (Kenney et al. 2004; Vollmer et al. 2004, 2006) to be moving at a high velocity (3500–4000 km s\(^{-1}\)) relative to the local ICM, either because it is not bound to the cluster or because the ICM itself is in motion due to the infall of the M49 group. The tail to lower velocities revealed by our observations indicates that it is certainly moving at a significantly higher recessional velocity than its local ICM. Gas removed from NGC 4522 would be expected to eventually come to rest at the velocity of the ICM, which could potentially explain the relatively flat velocity profile of the complex and its separation in velocity space from NGC 4522.

The simulations of Vollmer et al. (2006) find a best fit for an inclination of the galactic disk to the ICM wind of 60°, which gives a maximum line-of-sight component of the ICM wind of around 0.33. For the local ICM to be at the 500 km s\(^{-1}\) velocity, the complex would require this component to be around 0.46 for the highest relative velocity considered (4000 km s\(^{-1}\)). This would be possible for their 45° inclination simulation, which has a maximum line-of-sight component of around 0.56, but this simulation does not reproduce the observed extra-planar gas. It thus seems unlikely that the local ICM line-of-sight velocity in the region could be low enough to explain the complex as coming from NGC 4522.

In addition to this, and similarly to NGC 4424, NGC 4522 is currently being stripped and would thus also require two discrete stripping episodes. Putting all of these together, it seems unlikely that NGC 4522 is the parent galaxy for the complex.

5.3. Interactions

An alternative mechanism to ram pressure stripping for removing gas from galaxies is tidal interactions, which are thought to be responsible for some of the other dark clouds identified in the Virgo cluster. For example, the VIRGOHI 21 cloud, which is most likely to have been caused by a fairly extreme hyperbolic interaction (Bekki et al. 2005; Duc & Bournaud 2008; Taylor et al. 2017), has a mass of $2.2 \times 10^8 M_\odot$ (Minchin et al. 2005) with a total mass of the cloud and the stream connecting it to NGC 4254 of $4.3 \times 10^8 M_\odot$. 

Figure 9. Left: position–velocity map showing velocity as a function of R.A., covering the decl. range of 09° 11′–09°13′ (the range over which the tail is visible in the data cube), showing the tail to low velocities on NGC 4522 and the galaxy VCC 1437. Right: gray scale shows the Digitized Sky Survey image of the galaxy with blue contours showing the WAVES moment 0 map covering 2000–2200 km s\(^{-1}\) in velocity (i.e., only velocities below those of the main body of the galaxy) at $5 \times 10^{19}$ cm\(^{-2}\) and $1 \times 10^{20}$ cm\(^{-2}\), illustrating the eastwards extension of the tail from NGC 4522, and red contours showing the VLA moment 0 map from VIVA (Chung et al. 2007), covering around 2170–2470 km s\(^{-1}\), at $2 \times 10^{20}$, $5 \times 10^{20}$, $1 \times 10^{21}$, and $2 \times 10^{21}$ cm\(^{-2}\). The Arecibo beam is shown to the top left.

Figure 10. Spectrum of NGC 4522 summed over a 13′ × 7′ box centered on 12h33m30s, 09°12′00″ and primary-beam-corrected. A first-order (linear) baseline has been fitted and is shown; the extent of the spectrum indicates the region over which this fit was made. Dashed lines at 1945 and 2490 km s\(^{-1}\) indicate the area masked from the baseline fit and dotted lines at 1945 and 2180 km s\(^{-1}\) indicate the area used for the measurement of the tail.
Haynes et al. 2007. NGC 4254 itself, meanwhile, has an HI mass of $4.3 \times 10^9 M_\odot$ (Giovanelli et al. 2007). The event that created VIRGOHI 21 would thus appear to have removed around 5% of the mass of the parent galaxy into the compact cloud and a further 5% into the stream. Simulations by Taylor et al. (2017) show that, in multiple runs, the parent galaxy typically retains 90%–95% of its original gas content.

However, unlike ram pressure stripping which only affects the gas in a galaxy, tidal interactions have, in principle, equally strong effects on gas and stars. In practice, the gas disks of galaxies are usually very different from the stellar disks: the gas tends to be more extended than the stars but its density drops exponentially beyond the edge of the stellar disk (e.g., Broeils & Rhee 1997; Bigiel & Blitz 2012). This means that tidal encounters can disrupt the outermost gas without much affecting the stars, but since the density of this outer gas is low, such disruptions cannot remove significant amounts of gas. The only way for a tidal encounter to remove a high fraction of a galaxy’s gas content is if it is also strong enough to affect the inner, denser regions, which would necessarily also disrupt the stellar disk. Bekki et al. (2005), for example, found that in their simulations (with a model galaxy which followed Broeils & van Woerden 1994, in having a gas disk twice the size of the stellar disk) the mass fraction of stars within their isolated clouds was 14%–57%. Similarly, Taylor et al. (2017) found that there is not so much difference in the typical fraction of gas and stars that are stripped, with median fractions remaining in the disk of the parent galaxy of 92% for the gas and 95% for the stars. It does not seem likely that a tidal

| Cloud | Velocity Difference from C1 (km s$^{-1}$) | Projected Distance from C1 (kpc) | Timescale (Gyr) | Implied Dynamical Mass ($10^{10} M_\odot$) |
|-------|-----------------------------------------|---------------------------------|----------------|------------------------------------------|
| C2    | 111 ± 4                                 | 67                              | 0.6            | 19                                       |
| C2b   | 110 ± 7                                 | 68                              | 0.6            | 19                                       |
| C3    | 42 ± 3                                  | 88                              | 2.0            | 3.6                                      |
| C4    | 70 ± 4                                  | 38                              | 0.5            | 4.3                                      |
| C5    | 10 ± 4                                  | 87                              | 8.5            | 0.2                                      |
| C5b   | 189 ± 8                                 | 91                              | 0.5            | 76                                       |
| C6    | 42 ± 5                                  | 41                              | 1.0            | 17                                       |

(Haynes et al. 2007). NGC 4254 itself, meanwhile, has an HI mass of $4.3 \times 10^9 M_\odot$ (Giovanelli et al. 2007). The event that created VIRGOHI 21 would thus appear to have removed around 5% of the mass of the parent galaxy into the compact cloud and a further 5% into the stream. Simulations by Taylor et al. (2017) show that, in multiple runs, the parent galaxy typically retains 90%–95% of its original gas content.
interaction with another galaxy could remove most of the gas in a galaxy while leaving that galaxy intact optically, thus a galaxy the size of NGC 4445 or NGC 4424 could not be the parent galaxy in a tidal interaction scenario.

A more plausible alternative, in the abstract, might be to scale up the parent galaxy by an order of magnitude so the removal of $2\times 10^9 M_\odot$ or more is only a relatively small percentage of the total H I mass. This would, however, require a parent galaxy with a few times $10^{10} M_\odot$ of H I originally (90%-95% of which would be retained; Taylor et al. 2017), and a similarly massive interactor to pull the gas out—such galaxies do exist but are rare, and there are no candidates in this part of the Virgo cluster. We would expect that, as with VIRGOGI 21 and the simulations it inspired, at least the parent galaxy would still be relatively nearby, even if a hyperbolic interactor was now too distant to be identified. It thus seems unlikely that interactions can provide a plausible mechanism for the creation of the complex.

6. Conclusions

NGC 4522 can be ruled out as a likely source galaxy for the ALFALFA Virgo 7 complex. The galaxy, with its tail pointing toward the eastern end of the complex both spatially and in velocity, is the only large nearby galaxy with any hint of a connection to the complex, but its large velocity separation makes this association dubious at best. Earlier simulations (by Vollmer et al. 2006) that might have allowed the gas in the complex to have come to rest with respect to the local ICM do not successfully reproduce the extra-planar gas seen in this galaxy, and their simulations that do reproduce that gas place the recessional velocity of the local ICM near NGC 4522 significantly higher than that of the complex.

NGC 4445 is a possible source galaxy for the complex, while NGC 4424 is a less likely candidate. Our sensitive 21 cm map of the complex reveals a large reservoir of gas that was not detected by ALFALFA. This gas is found in low-velocity clouds associated with the C2 and C5 clouds of Kent et al. (2009), in a sixth cloud, termed C6, joined to the main body of the complex, and as low column-density gas between the clouds. Its detection raises the H I mass of the complex from $0.5 \times 10^9 M_\odot$ to $1.3 \times 10^9 M_\odot$; this counts against either NGC 4445 or NGC 4424 being a likely source galaxy for the complex. It is notable that NGC 4424 is currently being stripped, while NGC 4445 has lost much of its gas at some point in the past but is not currently thought to be undergoing stripping; it is possible that a single event in the past could have been responsible for this gas loss, from NGC 4445, potentially giving rise to the complex.

For the H I 1225+01 complex, Matsuoka et al. (2012) conclude that its formation process is still not well understood. We must similarly conclude that the origin of the ALFALFA Virgo 7 complex remains without a satisfactory solution—one of the obvious mechanisms normally invoked can explain the presence of an isolated $\sim 10^9 M_\odot$ neutral hydrogen complex in this location in the Virgo cluster. Our WAVES observations will cover the regions to the north and west of the complex over the next couple of years, which will allow us to identify any other gas clouds that might be associated with this complex and potentially give further clues toward its formation. As it stands, the least-worst candidate for the source galaxy remains NGC 4445, but this appears to require it to have been unusually gas-rich prior to the formation of the complex.

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