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A 500 kpc HI Extension of the Virgo Pair NGC4532/DDO137 Detected by the Arecibo Legacy Fast ALFA (ALFALFA) Survey

Rebecca A. Koopmann
Union College - Schenectady, NY, koopmanr@union.edu

Riccardo Giovanelli
Cornell University

Martha P. Haynes
Cornell University

Brian R. Kent
Cornell University

Thomas J. Balonek
Cornell University

See next page for additional authors

Authors

Rebecca A. Koopmann, Riccardo Giovanelli, Martha P. Haynes, Brian R. Kent, Thomas J. Balonek, Noah Brosch, James L. Higdon, John J. Salzer, and Oded Spector

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A 500 KPC HI EXTENSION OF THE VIRGO PAIR NGC4532/DDO137 DETECTED BY THE ARECIBO LEGACY FAST ALFA (ALFALFA) SURVEY

Rebecca A. Koopmann[1,2], Riccardo Giovanelli[2,3], Martha P. Haynes[2,3], Brian R. Kent[3], Thomas J. Balonek[2,4], Noah Brosch[5], James L. Higdon[6], John J. Salzer[7,8], and Oded Spector[5]

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ABSTRACT

We report the discovery of a ∼500 kpc HI extension southwest of the Virgo Cluster HI-rich pair NGC 4532/DDO 137, detected as part of the Arecibo Legacy Fast ALFA (ALFALFA) Survey. The feature is the longest and most massive HI tail structure so far found in the Virgo Cluster and, at 1.8 Mpc from M87, the most distant from the main concentration of the intracluster medium. The structure is spatially and spectrally separated into two ridges and is defined by diffuse emission and discrete clumps of mass 2.5 - 6.8 x 10^7 $M_\odot$. All emission is blue-shifted with respect to the NGC 4532/DDO 137 pair emission. Including diffuse emission, the structure has a total mass of up to 7 x 10^8 $M_\odot$, equivalent to ∼10% of the system's HI mass. Optical *R*-band imaging finds no counterparts to a level of 26.5 mag arcsec^{-2}. The characteristics of the structure appear most consistent with a tidal origin.

Subject headings: galaxies: spiral, galaxies: clusters: general, galaxies: clusters: individual (Virgo), galaxies: structure, galaxies: interactions, galaxies: evolution

1. INTRODUCTION

Galaxies in clusters experience a variety of environmental interactions that affect their evolution (see Boselli & Gavazzi 2006 for a review). Intracluster medium (ICM) interactions such as ram pressure stripping (Gunn & Gott 1972) and starvation (Larson, Tinsley, & Caldwell 1980) prematurely remove gaseous reservoirs. Tidal interactions, including nearby, slower encounters in cluster and group substructures (Toomre & Toomre 1972), nearby high velocity encounters (Duc & Bournaud 2008), and galaxy harassment (Moore *et al.* 1996, 1998; Bekki *et al.* 2005), rearrange stellar and gaseous contents. These interactions potentially explain the observed gas deficiencies (Giovanelli & Haynes 1983, Cayatte *et al.* 1990), reduced star formation (Kennicutt 1983; Koopmann & Kenney 2004), and morphology-density relation (Dressler 1980) in clusters.

Environmental interactions can produce low surface brightness stellar and gas tails. Chung *et al.* (2007) find one-sided HI tails in seven Virgo spirals, attributing them to the influence of the ICM. Oosterloo & van Gorkom (2005) report a 110 x 25 kpc plume of HI gas extending away from the HI-deficient Virgo spiral NGC 4388, also attributing the feature to ICM interaction. Mihos *et al.* (2005) find stellar streams associated with several presumably tidal events near the Virgo Cluster core. Similar features have been found in Coma and Centaurus (Gregg & West 2004). The characteristics of tail features are related to the details of the environmental interaction that produced them, helping to determine the relative importance of different interactions. Tidal tails may allow the formation of tidal dwarf galaxies, contributing to the dwarf galaxy population.

The Arecibo Legacy Fast ALFA (ALFALFA) Survey, a sensitive blind survey of the Arecibo sky (Giovanelli *et al.* 2005), is providing a complete and unbiased view of HI content and structures in the entire Virgo cluster region. The survey has revealed the presence of several HI clouds without optical components (Kent *et al.* 2007) and a 250 kpc extended tidal arc emerging from the Sc galaxy NGC 4254. This structure, encompassing the Virgo HI21 cloud (Minchin *et al.* 2007), is likely due to a high velocity close galaxy encounter (Haynes *et al.* 2007; Duc & Bournaud 2008).

In this Letter, we report the detection by ALFALFA of an even larger tidal feature associated with the Virgo Cluster pair NGC 4532/DDO 137. This pair of SmIII/SmIV (Binggeli, Sandage, & Tammann 1985) galaxies is located in the Virgo B Cloud (Binggeli, Popescu, & Tammann 1993), 6° south of the Virgo center. NGC 4532 is the brightest Sm cataloged in the

Electronic address: koopmanr@union.edu
Electronic address: riccardo@astro.cornell.edu
Electronic address: haynes@astro.cornell.edu
Electronic address: bkent@astro.cornell.edu
Electronic address: tbalonek@mail.colgate.edu
Electronic address: noah@wise.tau.ac.il
Electronic address: jhigdon@georgiasouthern.edu
Electronic address: slaz@astro.indiana.edu
Electronic address: odedspec@wise.tau.ac.il
[1] Union College, Department of Physics and Astronomy, Schenectady, NY 12308
[2] National Astronomy and Ionosphere Center, 530 Space Sciences Building, Ithaca, NY 14853. The National Astronomy and Ionosphere Center is operated by Cornell University under a cooperative agreement with the National Science Foundation, Cornell University.
[3] Center for Radiophysics and Space Research and National Astronomy and Ionosphere Center, 530 Space Sciences Building, Cornell University, Ithaca, NY 14853
[4] Department of Physics & Astronomy, Colgate University, Hamilton, NY 13346
[5] The Wise Observatory & the School of Physics and Astronomy, Raymond & Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Israel
[6] Department of Physics, Georgia Southern University, Statesboro, GA 30460
[7] Astronomy Department, Wesleyan University, Middletown, CT 06459
[8] Department of Astronomy, Indiana University, Bloomington, IN 47401

Virgo Cluster Catalog (Binggeli, Sandage & Tammann 1985; hereafter VCC) and has a high star formation rate (Koopmann & Kenney 2004) and an asymmetric stellar morphology. The galaxies share a common HI envelope extended over 150 kpc (Hoffman *et al.* 1992, 1993). Hoffman *et al.* (1999) found that the HI envelope contains three additional discrete HI clumps that have no optical counterparts as well as a significant diffuse HI component, some of which appeared as a tail-like extension to the southwest. We show that there is indeed an extended HI structure, stretching $\sim$ 500 kpc beyond the pair.

Section 2 describes ALFALFA and optical followup observations of the extended HI structure and Section 3 addresses possible formation mechanisms. We assume a Virgo Cluster distance of 16.7 Mpc (e.g., Mei *et al.* 2007) throughout.

2. OBSERVATIONS AND RESULTS

2.1. *ALFALFA*

The ALFALFA survey is mapping 7074 square degrees of the high galactic sky visible from Arecibo, using the 7-feed Arecibo L-band Feed Array (ALFA) on the 305 m antenna. The survey characteristics are documented by Giovanelli *et al.* (2005). ALFALFA can detect HI sources with $M_{HI} > 2 \times 10^7 (W_{50}/25)^{1/2} M_\odot$ at the Virgo cluster distance, where W_{50} is the velocity width of the source line profile, measured at 50% peak level, in km s^{-1} (Giovanelli *et al.* 2007; Kent *et al.* 2008). ALFALFA catalog data releases are accessible at http://arecibo.tc.cornell.edu/hiarchive/alfalfa/. The structure reported in this paper was found during survey data reduction and further studied using a (standard) 2.4° x 2.4° data cube centered at 12^h34^m+06°00′ [2000.0].

Figure 1a shows an integrated HI map of NGC 4532/DDO 137 and vicinity. The extended HI envelope surrounding the pair galaxies (Hoffman *et al.* 1992, 1993) is visible at upper left and the newly detected extended HI structure emerges from the southwest. In Figure 1b, intensity weighted HI velocity contours are superposed on the integrated HI map. (For detailed HI kinematics within the envelope surrounding the pair, see Hoffman *et al.* 1993, 1999). Extensive low HI column density ($N_{\rm HI}$) gas is apparent throughout this region in several channel maps, as shown in Figure 2.

We measure an HI mass of 6.0 x 10^9 $M_\odot$ for the HI envelope surrounding the pair, consistent with that of Hoffman *et al.* (1999). An additional HI mass of 1.3 x 10^8 $M_\odot$ is contained within a partially resolved clump $\sim$ 20′ west of NGC 4532, hereafter the 'western clump.' The HI extension is defined by discrete clumps as well as diffuse emission (Figure 2). Fluxes, velocities, and masses of the discrete clumps are presented in Table 1 (see Giovanelli *et al.* 2007 for details about determination of listed parameters). Clumps are numbered in order of their right ascension and their positions are labeled with these numbers in Figure 1a. Several of the clumps are marginally resolved by the ALFALFA beam and show elongated structure. Velocity widths of the clumps range from 34 to 112 km s^{-1}, values similar to those of low luminosity dwarf galaxies. Most clumps are single-peaked. Clump #8 coincides spatially and in velocity with the galaxy Tololo 1232+052, a dwarf galaxy (Mr = -15) with a blue color and prominent emission lines (SDSS; York *et al.* 2000), making it a tidal dwarf candidate.

All of the emission in the HI extension is blueshifted with respect to NGC 4532/DDO 137. Figure 1b shows that the velocity field is highly ordered. There are two ridges separated spectrally by about 100 km $s^{-1}$and spatially by about 10′ east-west. The eastern ridge is closest in velocity to the envelope surrounding NGC 4532/DDO137 and is similar in velocity to the hook-like feature emerging northeast of the envelope (see also Figure 2 of Hoffman *et al.* 1993). The western ridge, which includes the portion that extends south and then curves toward the east, extends to the lowest velocities in the system, overlapping spectrally with the western clump.

The total HI mass contained within discrete clumps is 3.9 x 10^8 $M_\odot$. Diffuse emission traces the ridges between the main clumps, with an HI mass of $\sim$1x10^8 $M_\odot$. An upper limit of $\sim$2 x 10^8 $M_\odot$ can be placed on the mass below the ALFALFA limiting $N_{\rm HI}$ of 3 x 10^{18} cm^{-2}, assuming a total area of 500 x 20 kpc. Thus the total mass in the structure has an upper limit 7 x 10^8 $M_\odot$, approximately 10% of the HI mass within the disks of the two galaxies in the pair.

2.2. *Optical Imaging*

Deep B- and R-band imaging of several fields in the HI extension was carried out at the 40-inch telescope at Wise Observatory on the nights of 18, 19, and 21 May, 2007, using the PI-CCD camera with a pixel scale of 0.6 arcsec pixel^{-1}. Additional fields were imaged in R-band at the WIYN 0.9m at Kitt Peak Observatory on the night of 21 May, 2007, using the S2KB CCD camera with pixel scale of 0.6 arcsec pixel^{-1}. Images were reduced in IRAF using standard procedures. Wise R-band images from 18 May and the WIYN R-band images reach a surface brightness level of 26.5 mag arcsec^{-2} and 25.5 mag arcsec^{-2}, respectively. Scattered light contaminates Wise R-band images in several fields. The B-band images reach a surface brightness level of $\sim$24.4 mag arcsec^{-2}, comparable to the SDSS. Faint galaxies visible in these fields either lack redshifts or are at high redshift (Sloan Digital Sky Survey; York *et al.* 2000) and few are good matches for the HI clump positions. Thus, with the exception of Tololo 1232+052, no dwarf galaxy-like sources (i.e., $M_{\rm B} \approx -15$, $D \approx 2-5$ kpc) are seen to coincide with the HI clumps in Figure 1a. No obvious extended optical emission is apparent in the smoothed images, though scattered light limits this analysis. Additional optical, HI synthesis, and GALEX followup observations are underway.

3. DISCUSSION

We have discovered an extremely long (500 kpc) HI stream of low $N_{\rm HI}$, dotted by higher density clumps appearing as isolated HI clouds, most with no optical counterpart, apparently associated with the galaxy pair NGC 4532/DDO 137. The characteristics of the system are reminiscent of those reported by Kent et al (2007), Haynes et al (2007), and Tripp (2007), also found mainly in the periphery of the Virgo cluster.

The feature is to our knowledge the most extreme HI tail structure found in a cluster, both in terms of its length and its position in the cluster. It is located at $\geq$1.6 times the distance from the Virgo Cluster center as other galaxies with tail features. The projected extent

TABLE 1
HI Sources in the NGC4532/DDO137 Stream

Source	α J2000	δ J2000	$cz_\odot$ (km s^{-1})	W_{50} (km s^{-1})	F_c (Jy km s^{-1})	S/N	M_{HI} (10^7 $M_\odot$)	Notes
Pair Complex	12 34 20.2	+06 27 51	2015 ± 1	163 ± 2	91.66 ± 0.08	170	602	
W Clump	12 33 36.9	+06 26 43	1804 ± 9	103 ± 18	1.99 ± 0.08	18	13	
1	12 32 18.6	+05 52 51	1833 ± 10	47 ± 20	1.03 ± 0.06	12.8	6.8	multiple peaks
2	12 32 39.8	+06 01 17	1803 ± 7	107 ± 14	0.74 ± 0.05	8.4	4.9	
3	12 33 05.3	+05 51 00	1915 ± 3	36 ± 8	0.98 ± 0.05	15.0	6.4	SW extension
4:	12 33 05.7	+05 26 00	1841 ± 13	76 ± 25	0.46 ± 0.06	5.2	3.0	uncertain detection
5	12 33 13.4	+05 02 47	1826 ± 2	35 ± 5	0.75 ± 0.05	10.6	4.9	multiple peaks
6	12 33 31.2	+06 09 30	1819 ± 9	113 ± 18	0.58 ± 0.05	6.3	3.8	
7	12 33 34.0	+06 02 59	1872 ± 6	110 ± 17	0.98 ± 0.11	8.6	6.4	multiple peaks
8	12 35 20.2	+05 02 00	1808 ± 4	35 ± 9	0.38 ± 0.05	5.4	2.5	assoc. w/ Tololo1232+052?

is a factor $\geq$ 14 times as large as the one-sided HI tails discovered in the VLA Imaging of Virgo Galaxies Survey (Chung *et al.* 2007). It is several times larger than the stellar tails found by Mihos *et al.* (2005) and Gregg & West (2004) and the HI tail described by Osterloo & Van Gorkom (2005), and twice as large as the feature near NGC 4254 (Haynes *et al.* 2007). The total HI mass is a factor of 1.5-16 times larger than that reported for other HI tails, although the fractional mass of ∼10% of the presumed host system is similar.

The NGC 4532/DDO 137 pair is located at a projected distance of 1.8 Mpc south of M87 and 0.5 Mpc southwest of M49 (NGC 4472). Binggeli *et al.* (1993) identify the galaxies as members of the Virgo B cloud, which is centered near M49 and lies at about the same distance as the more massive Virgo A Cloud centered near M87 (Binggeli *et al.* 1993; Mei *et al.* 2007). The subclump contains about ∼1% of the total ICM mass in the cluster (Schindler *et al.* 1999) and has a spiral-rich population with a mean line-of-sight velocity of ∼1040 km s^{-1} and a velocity dispersion of ∼500 km s^{-1} (Binggeli *et al.* 1993).

We estimate the ram pressure force due to the ICM at the position of NGC 4532/DDO 137 to be 2 - 25 times smaller than the gravitational restoring force on their ISM (following a similar approach as Chung *et al.* 2007 with dynamical properties of the galaxies given by Hoffman*et al.* 1999). The extended HI envelope is presumably less tightly bound and would be more susceptible to stripping. A challenge for an ICM interpretation is the length of the feature: it is an order of magnitude longer than other observed and simulated (e.g., Vollmer *et al.* 2001; Roediger & Brüggen 2008) features. In addition, it extends south of the pair, implying a trajectory that did not take the pair through the densest and hottest part of the ICM, as traced by ROSAT (Böhringer *et al.* 1994) and ASCA (Shibata *et al.* 2001).

Tidal interactions naturally produce long, gas-rich tails (e.g., Toomre & Toomre 1972). NGC 4532 and DDO 137 appear to be a bound pair and could be interacting. NGC 4532 shows other symptoms of tidal interaction: it is optically asymmetric and has a high star formation rate (Koopmann *et al.* 2004) and disturbed velocity field (Rubin *et al.*1999; Chemin *et al.* 2005; Hoffman *et al.* 1999). The HI extension described here displays a highly ordered velocity field. However low velocity tidal interactions between galaxies tend to produce symmetric tails of gas and stars (e.g., Toomre & Toomre 1972; Hibbard *et al.* 2001). In this case no stellar tail has yet been found and the HI extension and excess HI envelope gas not identified with the galaxies (Hoffman *et al.* 1999) display strong kinematic and spatial asymmetries.

These peculiarities could be consistent with a higher velocity encounter with another massive galaxy. Models of high velocity (∼ 1000 km s^{-1}) close galaxy encounters (Duc & Bournaud 2008) share some similarities to low velocity encounters, e.g., the length of the tail and the formation of dense clumps along tails, but produce lower mass, asymmetric, gas-dominated tails. Duc & Bournaud (2008) are able to reproduce the 250 kpc long HI tail extending northward from NGC 4254 (Haynes *et al.* 2007) via an encounter 750 Myr ago at a speed of 1100 km s^{-1} with a galaxy 50% more massive. There are ∼10 massive (M_B < -18.1) galaxies within 1.5° (440 kpc) of NGC 4532/DDO 137 and the HI extension, including M49 (NGC 4472) and 5 other galaxies identified with Virgo B (Binggeli *et al.* 1993). NGC 4532 and DDO 137 have line-of-sight velocities of ∼ 2000 km s^{-1} ($2\sigma \sim 1000$ km s^{-1} greater than Virgo B mean) so that a high speed encounter with a B member is possible. As argued by Duc & Bournaud (2008), the perturber may be further away; a galaxy moving at 1000 km s^{-1} can travel a projected distance of ∼ 1 Mpc in 1 Gyr. We note that ALFALFA observations, to date complete to +4°00′, show no other extended HI features associated with other galaxies in the vicinity.

Based upon the available models, we suggest that the structure associated with NGC 4532/DDO 137 is most consistent with a tidal interaction, possibly a high velocity encounter. Determining the exact nature of these very long HI tails and the extended HI envelope will require detailed simulation of the system in the entire Virgo Cluster environment, an exercise outside the scope of this paper.

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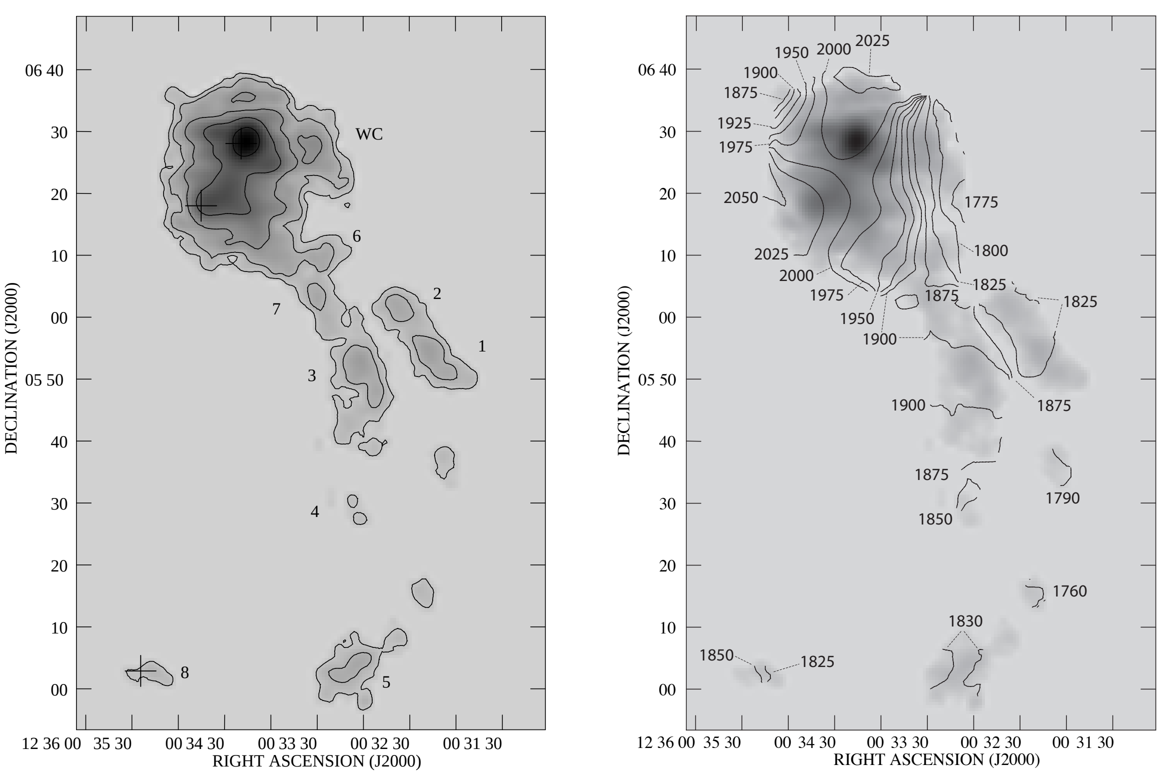

Fig. 1.— a. Integrated ALFALFA HI map of the NGC 4532/DDO 137 complex and extension after convolution with a 200" gaussian in the spatial dimension, shown in grey-scale (using a square-root transfer function) and with superposed contours. Contour levels are at 0.01, 0.03, 0.12, 0.49, 2.0 $M_\odot$ pc^{-2} (9.65 x 10^{17}, 3.86 x 10^{18}, 1.54 x 10^{19}, 6.18 x 10^{19}, 2.47 x 10^{20} cm^{-2}). Clumps are numbered according to their right ascension, as given in Table 1. 'WC' indicates the location of the western clump discussed in the text. Clump #8 coincides spatially and spectrally with the dwarf galaxy Tololo 1232+052 and is thus a candidate tidal dwarf galaxy. b. Intensity weighted HI velocity field for the NGC5241/DDO137 system. Isovelocity contours in units of km s^{-1} are superposed on the grey-scale integrated HI distribution. The velocity field in the HI extension is highly ordered and all of the emission in the extension is blueshifted with respect to the pair.

Fig. 2.— Smoothed (6′ FWHM) ALFALA channel maps of the NGC 4532/DDO 137 system showing extensive low $N_{\rm HI}$ gas. A square-root transfer function has been used, and the color-bar shows flux density in units of mJy beam^{-1}. The positions of NGC 4532 and DDO 137 are indicated by crosses. The scale bar corresponds to 100 kpc at the assumed distance of 16.7 Mpc.