CUME 336, given by R. Walterbos

This cume is partially based on the paper "A 500 kpc HI extension of the Virgo pair NGC4532/DDO 137 detected by the Arecibo fast ALFA (ALFALFA) survey", by Koopmann etal, 2008, ApJ 682, L85

Total possible score: 65, Passing score: 45. Make sure to try all the questions, only parts of questions 1 and 2 require you to remember the details on HI line emission.

Suggested time allocation:
Reading the questions and paper: 15-30 min
Question 1: 10-15 min
Question 2: 15- 20 min
Question 3: 30-45 min
Question 4: 10-20 min

1. Short questions (5 pts each)
a. What line transition for HI was observed in this survey (give wavelength and frequency).

b. What is the origin of this line (i.e. which transition causes the line to be emitted)?

c. Calculate the theoretical angular resolution that the Arecibo telescope can achieve at the observed frequency. If you did not get the answer to question 1a, give the formula.

d. The caption for Figure 2 mentions "...smoothed (6' FWHM)...". What is meant with "smoothed" and "FWHM"?

2. (15 pts) The paper discusses HI masses for various features. How, in general, is the HI mass derived from the HI observations? Sketch the various steps that need to be done, and list the major assumptions that are required. To help guide your answer, here are some things I will be looking for:

- How is the upper energy state for this line excited? What statistical distribution describes the population of the two energy levels?
- Does the emission depend on the temperature of the HI gas? (Hint: contrast kT with $h\nu$)
- How do I go from detected intensity (or flux) to mass?
- How does the derived mass depend on the assumed distance to the object?

3 (20 pts total)
a. The paper lists the properties of various HI clumps in Table 1. For clump 8, they state in the paper that there is a possible optical counterpart, a dwarf galaxy, with an absolute magnitude in r of -15. Apparently, this is a rather blue galaxy. Given that it is rather blue, would it have an overall lower or higher mass to light ratio than stars like the Sun? Explain your answer.

b. For the Sun, $M_r = 4.3$. Calculate an estimate of the mass in stars for this galaxy assuming the overall mass to light ratio is the same as for the Sun. How does this estimate of the mass in stars compare to the mass in HI? *(Hint: call the mass to light ratio equal to 1 for the Sun, and work in relative units, do not plug in actual values for the mass in g or luminosity in erg/sec for the Sun. Give the answer in solar masses).*

c. Let's assume the galaxy is about 2 kpc in radius, and that the HI line width in Table 1 allows us to constrain the circular orbital velocity of the gas at this radius. Calculate a dynamical mass interior to 2 kpc. Comment on any difference with the mass from 3a and what might cause this.

d. The authors also discuss searches for other optical counterparts and quote a limit in surface brightness of 26.5 mag/arcsec^2 in the red. How big would the dwarf galaxy in problem 3a be if it had such an average low surface brightness? Assume the galaxy is circular and give the answer both as an angular measure and as a linear size in kpc. *Hint: it will be useful as the first step to convert the absolute magnitude to an apparent magnitude for the distance given in the paper (16.7 Mpc).*

4. (10 pts) In the discussion section, the authors discuss two possible mechanisms responsible for creating the HI features. What are they, and how do they work, i.e. what physical parameters do each of them depend on (I am not looking for long equations, just a few basic dependencies)?

Astronomical Constants		
Solar mass	1 $M_\odot$	$= 1.989 \times 10^{33}$ g
Solar luminosity	1 $L_\odot$	$= 3.826 \times 10^{33}$ ergs s^{-1}
Solar radius	1 $R_\odot$	$= 6.9599 \times 10^{10}$ cm
Solar effective temperature	$T_\odot$	$= 5770$ K
Earth mass	1 $M_\oplus$	$= 5.974 \times 10^{27}$ g
Earth radius	1 $R_\oplus$	$= 6.378 \times 10^{8}$ cm
Light year	1 ly	$= 9.4605 \times 10^{17}$ cm
Parsec	1 pc	$= 3.0857 \times 10^{18}$ cm
		$= 3.2616$ ly
Astronomical unit	1 AU	$= 1.4960 \times 10^{13}$ cm
Sidereal day		$= 23^h\ 56^m\ 04.09054^s$
Solar day		$= 86400$ s
Sidereal year		$= 3.155815 \times 10^{7}$ s
Tropical year		$= 3.155693 \times 10^{7}$ s

Physical Constants		
Gravitational constant	G	$= 6.67259 \times 10^{-8}$ dyne $cm^2\ g^{-2}$
Speed of light (exact)	c	$= 2.99792458 \times 10^{10}$ cm s^{-1}
Planck's constant	h	$= 6.6260755 \times 10^{-27}$ erg s
	$\hbar$	$\equiv h/2\pi$
		$= 1.05457266 \times 10^{-27}$ erg s
Boltzmann's constant	k	$= 1.380658 \times 10^{-16}$ erg K^{-1}
Stefan–Boltzmann constant	σ	$= 5.67051 \times 10^{-5}$ erg $cm^{-2}\ s^{-1}\ K^{-4}$
Radiation constant	a	$= 4\sigma/c$
		$= 7.56591 \times 10^{-15}$ erg $cm^{-3}\ K^{-4}$
Proton mass	m_p	$= 1.6726231 \times 10^{-24}$ g
Neutron mass	m_n	$= 1.674929 \times 10^{-24}$ g
Electron mass	m_e	$= 9.1093897 \times 10^{-28}$ g
Hydrogen mass	m_H	$= 1.673534 \times 10^{-24}$ g
Atomic mass unit	1 u	$= 1.6605402 \times 10^{-24}$ g
		$= 931.49432\ \mathrm{MeV}/c^2$
Coulomb law constant (cgs)	k_C	$\equiv 1$
(SI)		$= 8.9875518 \times 10^{9}$ N $m^2\ C^{-2}$
Electric charge (cgs)	e	$= 4.803206 \times 10^{-10}$ esu
(SI)		$= 1.60217733 \times 10^{-19}$ C
Electron volt	1 eV	$= 1.60217733 \times 10^{-12}$ erg
Avagadro's number	N_A	$= 6.0221367 \times 10^{23}$ $mole^{-1}$
Gas constant	R	$= 8.314510 \times 10^{7}$ ergs $mole^{-1}\ K^{-1}$
Bohr radius	a_o	$= \hbar^2/m_e e^2$
		$= 5.29177249 \times 10^{-9}$ cm
Rydberg constant	R_H	$= \mu e^4/4\pi\hbar^3 c$
		$= 1.09677585 \times 10^{5}$ cm^{-1}

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A 500 kpc H I EXTENSION OF THE VIRGO PAIR NGC 4532/DDO 137 DETECTED BY THE ARECIBO LEGACY FAST ALFA (ALFALFA) SURVEY

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ABSTRACT

We report the discovery of a ~500 kpc H I extension southwest of the Virgo Cluster H I–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 H I 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 $(2.5–6.8) \times 10^7 M_\odot$. All emission is blueshifted with respect to the NGC 4532/DDO 137 pair emission. Including diffuse emission, the structure has a total mass of up to $7 \times 10^8 M_\odot$, equivalent to ~10% of the system's H I 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: clusters: general — galaxies: clusters: individual (Virgo) — galaxies: evolution — galaxies: interactions — galaxies: spiral — galaxies: structure

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 et al. 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 H I tails in seven Virgo spirals, attributing them to the influence of the ICM. Oosterloo & van Gorkom (2005) report a 110 × 25 kpc plume of H I gas extending away from the H I–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 H I content and structures in the entire Virgo Cluster region.[9] The survey has revealed the presence of several H I 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 VIRGOHI 21 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 Sm III/Sm IV (Binggeli et al. 1985) galaxies is located in the Virgo B Cloud (Binggeli et al. 1993), 6° south of the Virgo center. NGC 4532 is the brightest Sm cataloged in the Virgo Cluster Catalog (Binggeli et al. 1985) and has a high star formation rate (Koopmann & Kenney 2004) and an asymmetric stellar morphology. The galaxies share a common H I envelope extended over 150 kpc (Hoffman et al. 1992, 1993). Hoffman et al. (1999) found that the H I envelope contains three additional discrete H I clumps that have no optical counterparts as well as a significant diffuse H I component, some of which appeared as a taillike extension to the southwest. We show that there is indeed an extended H I structure, stretching ~500 kpc beyond the pair.

Section 2 describes ALFALFA and optical follow-up observations of the extended H I structure, and § 3 addresses possible formation mechanisms. We assume a Virgo Cluster distance of 16.7 Mpc (e.g., Mei et al. 2007) throughout.

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2. OBSERVATIONS AND RESULTS

2.1. *ALFALFA*

The ALFALFA survey is mapping 7074 deg^2 of the high Galactic sky visible from Arecibo, using the seven-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 H I sources with $M_{\rm H\,I} > 2 \times 10^7 (W_{50}/25)^{1/2}\ M_\odot$ 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).[10] The structure reported in this Letter was found during survey data reduction and further studied using a (standard) 2.4° × 2.4° data cube centered at α(J2000.0) = 12^{h}34^m, δ(J2000.0) = +06°00′.

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

We measure an H I mass of 6.0 × 10^9 $M_\odot$ for the H I envelope surrounding the pair, consistent with that of Hoffman et al. (1999). An additional H I mass of 1.3 × 10^8 $M_\odot$ is contained within a partially resolved clump ~20′ west of NGC 4532, hereafter the "western clump." The H I extension is defined by discrete clumps as well as diffuse emission (Fig. 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 1*a*. 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 ($M_r = -15$) with a blue color and prominent emission lines (Sloan Digital Sky Survey [SDSS]; York et al. 2000), making it a tidal dwarf candidate.

All of the emission in the H I extension is blueshifted with respect to NGC 4532/DDO 137. Figure 1*b* 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/DDO 137 and is similar in velocity to the hooklike feature emerging northeast of the envelope (see also Fig. 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 H I mass contained within discrete clumps is 3.9 × 10^8 $M_\odot$. Diffuse emission traces the ridges between the main clumps, with an H I mass of ~1 × 10^8 $M_\odot$. An upper limit of ~2 × 10^8 $M_\odot$ can be placed on the mass below the ALFALFA limiting $N_{\rm H\,I}$ of 3 × 10^{18} cm^{-2}, assuming a total

[10] ALFALFA catalog data releases are accessible at http://arecibo.tc.cornell.edu/hiarchive/alfalfa/.

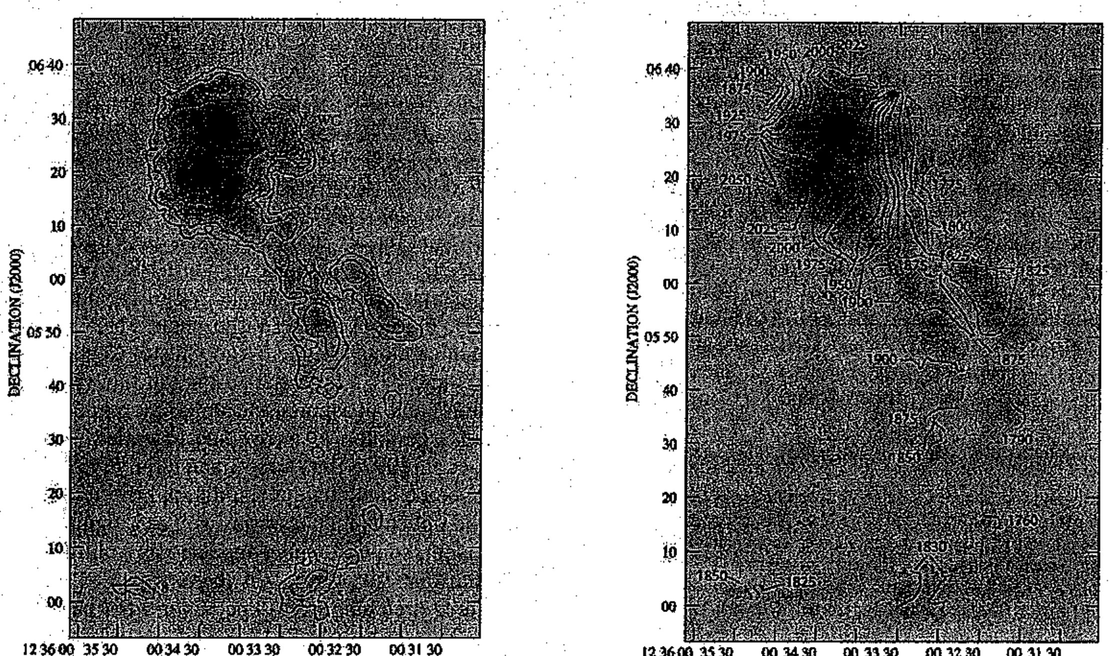

FIG. 1.—(*a*) Integrated ALFALFA H I map of the NGC 4532/DDO 137 complex and extension after convolution with a 200″ Gaussian in the spatial dimension, shown in gray scale (using a square-root transfer function) and with superposed contours. Contour levels are at 0.01, 0.03, 0.12, 0.49, 2.0 $M_\odot$ pc^{-2} (9.65 × 10^{17}, 3.86 × 10^{18}, 1.54 × 10^{19}, 6.18 × 10^{19}, 2.47 × 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 H I velocity field for the NGC5241/DDO 137 system. Isovelocity contours in units of km s^{-1} are superposed on the gray-scale integrated H I distribution. The velocity field in the H I extension is highly ordered, and all of the emission in the extension is blueshifted with respect to the pair.

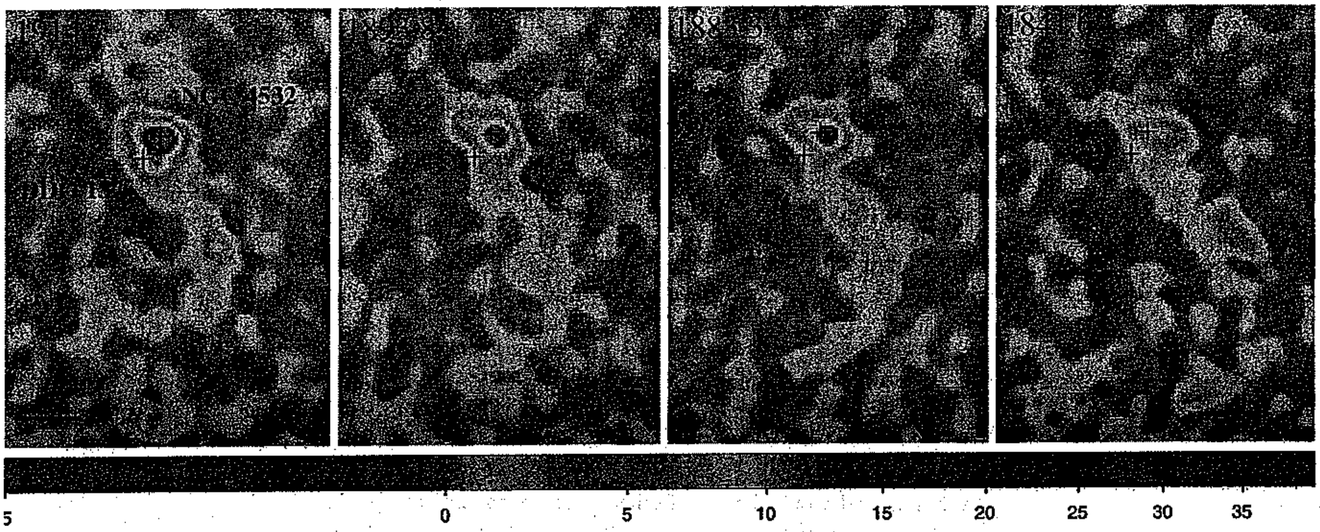

FIG. 2.—Smoothed (6′ FWHM) ALFALA channel maps of the NGC 4532/DDO 137 system showing extensive low $N_{\rm H\,I}$ gas. A square-root transfer function has been used, and the color bar shows flux density in units of mJy beam^{-1}. The positions of NGC 4532 and DDO 137 are indicated by crosses. The scale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

area of 500 × 20 kpc. Thus, the total mass in the structure has an upper limit of $7 \times 10^8\ M_\odot$, approximately 10% of the H I 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 H I extension was carried out at the 40 inch telescope at Wise Observatory on the nights of 2007 May 18, 19, and 21, 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 0.9 m at Kitt Peak Observatory on the night of 2007 May 21, 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 ~24.4 mag arcsec^{-2}, comparable to the SDSS. Faint galaxies visible in these fields either lack redshifts or are at high redshift (SDSS; York et al. 2000), and few are good matches for the H I clump positions. Thus, with the exception of Tololo 1232+052, no dwarf galaxy–like sources (i.e., $M_B \approx -15$, $D \approx 2$–5 kpc) are seen to coincide with the H I clumps in Figure 1*a*. No obvious extended optical emission is apparent in the smoothed images, although scattered light limits this analysis. Additional optical, H I synthesis, and *GALEX* follow-up observations are underway.

3. DISCUSSION

We have discovered an extremely long (500 kpc) H I stream of low $N_{\rm H\,I}$, dotted by higher density clumps appearing as isolated H I 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 (2008), also found mainly in the periphery of the Virgo Cluster.

The feature is to our knowledge the most extreme H I tail structure found in a cluster, in terms of both its length and its position in the cluster. It is located at ≥1.6 times the distance from the Virgo Cluster center as other galaxies with tail features. The projected extent is a factor ≥14 times as large as the one-sided H I 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 H I tail described by Osterloo & Van Gorkom (2005), and twice as large as the feature near NGC

TABLE 1
H I SOURCES IN THE NGC 4532/DDO 137 STREAM

Source	α(J2000.0)	δ(J2000.0)	$cz_\odot$ (km s^{-1})	W_{50} (km s^{-1})	F_c (Jy km s^{-1})	S/N	$M_{\rm H\,I}$ ($10^7\ M_\odot$)	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	Associated with Tololo1232+052?

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

4254 (Haynes et al. 2007). The total H I mass is a factor of 1.5–16 times larger than that reported for other H I 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 H I 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 & Kenney 2004) and disturbed velocity field (Rubin et al. 1999; Chemin et al. 2005; Hoffman et al. 1999). The H I 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 H I extension and excess H I 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 H I 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 H I extension, including M49 (NGC 4472) and five 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 σ ~ 1000 km s^{-1} greater than Virgo B mean), so a high-speed encounter with a B member is possible. As argued by Duc & Bournaud (2008), the perturber may be farther 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 $\delta = +4°00'$, show no other extended H I features associated with other galaxies in the vicinity.

Based on 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 H I tails and the extended H I envelope will require detailed simulation of the system in the entire Virgo Cluster environment, an exercise outside the scope of this Letter.

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CUME 336, given by R. Walterbos

This cume is partially based on the paper "A 500 kpc HI extension of the Virgo pair NGC4532/DDO 137 detected by the Arecibo fast ALFA (ALFALFA) survey", by Koopmann etal, 2008, ApJ 682, L85

Total possible score: [illegible], Passing score: 65. Make sure to try all the questions, only parts of questions 1 and 2 require you to remember the details on HI line emission.

Suggested time allocation:
Reading the questions and paper: 15-30 min
Question 1: 10-15 min
Question 2: 15- 20 min
Question 3: 30-45 min
Question 4: 10-20 min

1. Short questions (5 pts each)
a. What line transition for HI was observed in this survey (give wavelength and frequency).

[Given that the paper is based on radio observations with Arecibo, the only possibly line is the HI 21-cm line at 1420 MHz.]

b. What is the origin of this line (i.e. which transition causes the line to be emitted)?

[The 21-cm line is due to the "spin-flip" transition, which is a reversal of the electron's spin to the proton's spin. The high energy state is that of "parallel" spins, while the low energy state is anti-parallel spins.]

c. Calculate the theoretical angular resolution that the Arecibo telescope can achieve at the observed frequency. If you did get the answer to question 1a, give the formula.

[1.2 (lamdba)/Diameter gives 2.9 arcmin FWHM.]

d. The caption for Figure 2 mentions "...smoothed (6' FWHM)...". What is meant with "smoothed" and "FWHM"?

["smoothed" means convolved with a (likely Gaussian) function to get the 6' FWHM beam rather than the 2.9' beam. Smoothing is done to increase S/N for features that are more extended than the beam. FWHM = full with at half maximum]

2. (15 pts) The paper discusses HI masses for various features. How, in general, is the HI mass derived from the HI observations? Sketch the various steps that need to be done, and list the major assumptions that are required. To help guide your answer, here are some things I will be looking for:

-How is the upper energy state for this line excited? What statistical distribution describes the population of the two energy levels?
-Does the emission depend on the temperature of the HI gas? (Hint: contrast kT with hυ)

- How do I go from detected intensity (or flux) to mass?
- How does the derived mass depend on the assumed distance to the object?

[This is standard ISM fare. The following items provide a full answer, though I certainly don't expect the students to remember it in this detail.
- The 21-cm line is excited by collisions amongst the atoms.
- We can assume therefore that the energy level populations are governed by Boltzman statistics since the velocity distribution of the gas that is responsible for the collisional excitations is given by the Maxwell-Boltzman distribution and collisions dominate the level populations, not radiative de-excitation.
- 21 cm line has $h\upsilon << kT$ *which means that for any physically plausible temperature for the HI gas, a fixed fraction of the HI atoms will be in the upper state (this follows from the Boltzman level populations). This implies that the emission coefficient for the 21-cm line is independent of temperature, and linearly correlated with the total HI density.*
- Under the assumption of optically thin 21-cm emission, the intensity of the 21-cm line is thus proportional to the column density of HI atoms along the line of sight.
- Integrating the intensity over the solid angle for any feature gives a total flux that is then converted into mass if we know the distance to the source.
- The derived mass depends on the distance squared to the object, since we must convert angular area to linear area.]

3 (~~15~~ 20 pts total)
a. The paper lists the properties of various HI clumps in Table 1. For clump 8, they state in the paper that there is a possible optical counterpart, a dwarf galaxy, with an absolute magnitude in r of -15. Apparently, this is a rather blue galaxy. Given that it is rather blue, would it have an overall lower or higher mass to light ratio than stars like the Sun? Explain your answer.

[A bluer color suggests that the light is dominated by a relatively young population. Younger stars are more massive and hotter and produce more light for a given mass than older stars. Hence one might expect the mass-to-light ratio to be low overall for a galaxy that is dominated by young stars. Galaxy light in general is dominated by light from A-F main sequence stars and/or red giants. The typical M/L for an older population is between a few to 10 or so. A M/L ratio of 1 (the value for the Sun) is indicative of a young population so it is in the overall ballpark here. Note that while the Sun is not a very young star, its M/L is low because normal galaxy light is not dominated by solar type main sequence stars.]

b. For the Sun, $M_r = 4.3$. Calculate an estimate of the mass in stars for this galaxy assuming the overall mass to light ratio is the same as for the Sun. How does this estimate of the mass in stars compare to the mass in HI? *(Hint: call the mass to light ratio equal to 1 for the Sun, and work in relative units, do not plug in actual values for the mass in g or luminosity in erg/sec for the Sun. Give the answer in solar masses).*

[Turn absolute magnitude of -15 in r into a number of solar-type stars given the magnitude of the Sun. The answer is $5.3x10^7$ *solar luminosities, so for M/L =1, a mass of the same number, about twice the mass of the HI.]*

c. Let's assume the galaxy is about 2 kpc in radius, and that the HI line width in Table 1 allows us to constrain the circular orbital velocity of the gas at this radius. Calculate a dynamical mass interior to 2 kpc. Comment on any difference with the mass from 3a and what might cause this.

[From the line width in the table (35 km/s) we can estimate a circular velocity of about 17 km/s. For a radius of 2 kpc this implies an enclosed mass GM(r)/r = $1.34x10^8$ solar masses. Of course this is just a guess given the assumed 2 kpc radius, but I would like the students to comment that our M/L ratio for the stars may well be wrong and/or that the galaxy is likely dominated by dark matter.]

d. The authors also discuss searches for other optical counterparts and quote a limit in surface brightness of 26.5 mag/arcsec^2 in the red. How big would the dwarf galaxy in problem 3a be if it had such an average low surface brightness? Assume the galaxy is circular and give the answer both as an angular measure and as a linear size in kpc. Hint: it will be useful as the first step to convert the absolute magnitude to an apparent magnitude for the distance given in the paper (16.7 Mpc).

[The surface brightness integrated over solid angle gives the flux; hence we first need to convert the absolute magnitude of -15 to an apparent magnitude at the stated distance. The distance given in the paper is 16.7 Mpc, so the apparent magnitude is 16.1 (from m-M=5 log(d) -5). Compare 26.5 mag/arcsec^2 to 16.1 to get a total area in arcsec^2, then derive a linear size in arcsec and from that a linear diameter. We get 14,500 arcsec^2. So the linear angular size is 120 arcsec, and the actual linear diameter at 16.7 Mpc is 9.7 kpc .]

4. (10 pts) In the discussion section, the authors discuss two possible mechanisms responsible for creating the HI features. What are they, and how do they work, i.e. what physical parameters do each of them depend on (I am not looking for long equations, just a few basic dependencies)?

[I do not expect much detail here. The two mechanisms are ram pressure stripping and tidal forces. The ram pressure depends on the density of the surrounding gas in the environment times the velocity of the HI clouds squared. The HI clouds are presumable kept together by gravity, so whether ram pressure is effective depends on the velocity of the clouds, the surrounding density, and the self-gravity. Tidal forces are caused by a difference in gravitational force between the front and back sides of the HI features and the galaxy(ies) present. In general, tidal forces will cause spherical objects to become elongated, the level of elongations again depending on the strength of the tidal force compared to the self gravity.]