

NGC 4254: AN ACT OF HARASSMENT UNCOVERED BY THE ARECIBO LEGACY FAST ALFA SURVEY

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ABSTRACT

We present an H I map constructed from the Arecibo Legacy Fast ALFA survey of the surroundings of the strongly asymmetric Virgo Cluster Sc galaxy NGC 4254. Noted previously for its lopsided appearance, rich interstellar medium, and extradisk H I emission, NGC 4254 is believed to be entering the Virgo environment for the first time and at high speed. The ALFALFA map clearly shows a long H I tail extending ~ 250 kpc northward from the galaxy. Embedded as one condensation within this H I structure is the object previously identified as a “dark galaxy” by Davies et al.: VIRGOHI 21. A body of evidence including its location within and velocity with respect to the cluster and the appearance and kinematics of its strong spiral pattern, extradisk H I, and lengthy H I tail is consistent with a picture of “galaxy harassment” as proposed by Moore et al. The smoothly varying radial velocity field along the tail as it emerges from NGC 4254 can be used as a timing tool, if interpreted as resulting from the coupling of the rotation of the disk and the collective gravitational forces associated with the harassment mechanism.

Subject headings: galaxies: clusters: individual (Virgo Cluster) — galaxies: halos — galaxies: interactions — intergalactic medium — radio lines: galaxies

1. INTRODUCTION

Because of its proximity and relative richness, the Virgo Cluster provides an especially useful laboratory for witnessing in detail the impact of environment on galaxy evolution. In Virgo, studies of the H I deficiency first quantified the impact of the cluster environment (Davies & Lewis 1973; Chamaraux et al. 1980), while subsequent mapping of the gas distribution proved that the H I disks of the highly gas-poor objects were systematically smaller than those of galaxies with normal H I content (Giovanelli & Haynes 1983; Cayatte et al. 1990). Further H I synthesis observations, most recently those of the VLA Imaging of Virgo Galaxies survey (Chung et al. 2007), yield details of the H I distribution in a growing selection of Virgo galaxies. Concurrently, the Arecibo Legacy Fast ALFA (ALFALFA) survey is conducting a sensitive blind H I survey of the entire Virgo Cluster region, identifying a host of H I features that are not coincident with stellar counterparts (Kent et al. 2007). The combined picture provided by both the blind and targeted H I surveys of Virgo promise to allow evaluation of the relative importance of interaction processes likely at work in the Virgo environment due to both gravitational and hydrodynamic forces.

NGC 4254 (M99) is a bright Sc galaxy located 3.7° to the northwest of M87. Bingeli et al. (1987) assigned it membership in the main Virgo A Cluster, so its projected separation from M87 is ~ 1 Mpc for a Virgo distance of 16.7 Mpc (Mei et al. 2007). Its heliocentric velocity of 2404 km s^{-1} implies a velocity of $\sim 1300 \text{ km s}^{-1}$ with respect to the cluster overall. It has no close neighbors but is noted for its strong $m = 1$ asymmetric spiral pattern and vigorous star formation, especially in its bright southern arm. NGC 4254 has been the subject of numerous detailed studies, most of which focus on the generation of its unusual optical lopsidedness by interaction with the cluster environment.

Of relevance to the present discussion, Davies et al. (2004) reported the detection, later confirmed via corroborating Arecibo observations (Minchin et al. 2005a), of $2.2 \times 10^8 M_\odot$ of H I at a position some 120 kpc north of NGC 4254. H I emission was detected in a total of five adjacent Arecibo pointings, spaced at intervals of $2.7'$ and centered on $(\alpha, \delta)_{\text{J2000.0}} = (12^{\text{h}}17^{\text{m}}53.6^{\text{s}}, +14^\circ45'25'')$. Based on the Arecibo observations, especially the relatively broad H I line width of 220 km s^{-1} , and the lack of detectable H I in a VLA synthesis map, they argued that VIRGOHI 21 is the disk of a large (>16 kpc in diameter), optically dark galaxy with a much larger total mass than that of the H I itself (Minchin et al. 2005b). They noted that VIRGOHI 21 lies about 120 kpc from both NGC 4262 and NGC 4254 but argued against any tidal connection with either, because of both the relatively large separation and their high relative velocity.

In this Letter we exploit the wide-field H I maps of the ALFALFA survey to detail a long complex of H I clouds, extending from NGC 4254 northward. VIRGOHI 21 is shown to be one condensation within this H I tail. Deeper observations subsequently undertaken at Arecibo allow us to trace the H I to a distance of ~ 250 kpc to the north of NGC 4254. In § 2 we describe the ALFALFA data and follow-up Arecibo observations. In § 3 we discuss the body of evidence regarding NGC 4254 in terms of the galaxy harassment scenario of Moore et al. (1996a, 1996b, 1998). All coordinates are for equinox J2000.0.

2. OBSERVATIONS AND ANALYSIS

The region around NGC 4254 and VIRGOHI 21 has been mapped as part of the ALFALFA survey program. ALFALFA is a two-pass survey which uses the Arecibo L-band Feed Array (ALFA) on the 305 m antenna. The ALFALFA observing strategy and data-processing pipeline were outlined in Giovanelli et al. (2005). Once both passes of the survey are completed, three-dimensional spectral line data cubes are constructed and a signal extraction algorithm, discussed in Saintonge (2007), is applied for preliminary identification of H I sources. H I sources in the northern part of Virgo were included in the first ALFALFA catalog release (Giovanelli et al. 2007), covering $+12^\circ < \delta < +16^\circ$. That tabulation includes 17 H I detections

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within 1° of VIRGOHI 21 ($\alpha = 12^{\text{h}}18^{\text{m}}, \delta = +14^\circ44'$) and at velocities $c_z < 3000 \text{ km s}^{-1}$. Of the 17 H I sources, four have no optical counterparts; three of those are extended (in comparison with the $3.3' \times 3.8'$ Arecibo telescope beam) and appear associated with the NGC 4254–VIRGOHI 21 system, while the remaining one is probably a foreground Milky Way high-velocity cloud.

Figure 1 (*left*) shows the integrated H I flux density contours as detected in the ALFALFA data set overlaid on the second-generation Digital Sky Survey (DSS2) blue image in the vicinity north of NGC 4254. The H I emission is integrated over the range $c_z = 1946\text{--}2259 \text{ km s}^{-1}$ for the stream and $c_z = 2259\text{--}2621$ for the galaxy on a grid with $1'$ spacing. The velocity cut for the stream is outside the $2250\text{--}2510 \text{ km s}^{-1}$ range reported in VLA maps of NGC 4254 (Vollmer et al. 2005). The superposed circle at $\alpha = 12^{\text{h}}17^{\text{m}}53.6^{\text{s}}, \delta = +14^\circ45'25''$ indicates the centroid of VIRGOHI 21 as reported by Minchin et al. (2005a). H I features connect in a stream that appears to emanate from NGC 4254.

In order to confirm the extended nature of the stream and, with higher signal-to-noise ratio, explore the velocity field along it, a set of H I spectra were obtained along the ridge of the H I stream with longer dwell times than those of the ALFALFA survey. Thirty-six on/off pairs were taken at $1.5'$ steps in declination, centered on the peak emission indicated by the ALFALFA data, using the single-beam L-band wide (LBW) receiver of the Arecibo telescope. Difference spectra were then constructed from each pair, with 2048 channels per polarization covering a 25 MHz band centered at 1410 MHz with a spectral resolution of 12.2 kHz (2.6 km s^{-1} at $c_z = 2000 \text{ km s}^{-1}$). The integration times varied from 3 to 6 minutes on source, depending on the expected signal strength, yielding an rms noise per channel of better than $\sim 2.6 \text{ mJy}$ before any spectral smoothing. These observations were about twice as sensitive as those obtained through ALFALFA.

The locations of the LBW pointings are illustrated by the filled circles superposed along the peak of the stream illustrated in Figure 1 (*left*). The peak velocity at each pointing for which the detected signal is significant is indicated on the position-velocity diagram in the right panel. Emission was detected in 27 of the 36 positions targeted by the LBW observations. The stream clearly connects to NGC 4254 in velocity space.

Giovanelli et al. (2007) give an H I mass for NGC 4254 itself of $4.3 \times 10^9 M_\odot$. The total H I line flux associated with gas in the extended stream, including the clumps reported by Giovanelli et al. (2007) and lesser ones near the ALFALFA detection limit, is 6.5 Jy km s^{-1} , which corresponds to $M_{\text{H I}} \sim 4.3 \times 10^8 M_\odot$. Given the extended nature of the source, the ALFALFA observations miss detecting any diffuse emission at column densities below the ALFALFA limit. Assuming that diffuse emission is present at column densities equal to or less than $3 \times 10^{18} \text{ H I atoms cm}^{-2}$ over a solid angle of 200 arcmin^2 , up to an additional $1.1 \times 10^8 M_\odot$ of H I may be present in the stream, bringing the total H I mass to $(5.0 \pm 0.6) \times 10^8 M_\odot$. The H I tail can be traced over $\sim 50'$, which at the Virgo distance corresponds to 242 kpc. This length is certainly dramatic, but not unique. Of comparable length is the longest of the stellar streams in the extended halo of M87, which was detected in very deep images of Virgo by Mihos et al. (2005).

3. DISCUSSION

By many measures, NGC 4254 is an exceptional Sc galaxy, one of the brightest spirals in the Virgo A Cluster. Its rare

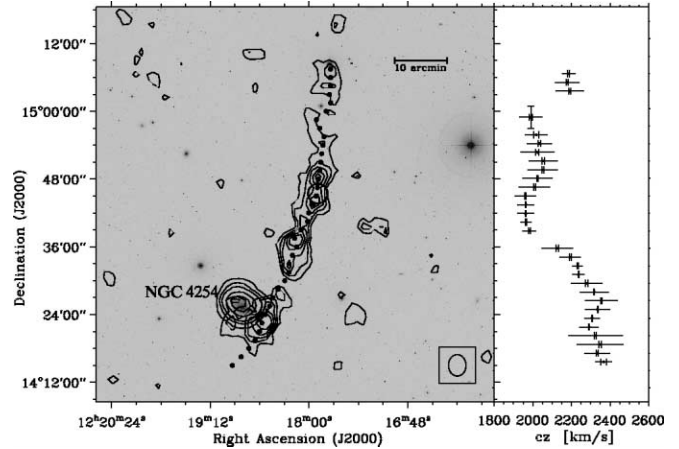


FIG. 1.—*Left*: H I flux contours extracted from the ALFALFA survey data set, which mapped the full field represented in the image, superposed on a DSS2 blue image. The 36 filled circles indicate the locations of beam centers for the successive LBW observations. The contours centered on NGC 4254 are at 10, 15, 20, 30, and $40 \text{ Jy beam}^{-1} \text{ km s}^{-1}$, integrated from 2259 to 2621 km s^{-1} . The contours for the H I stream are at 0.35, 0.52, 0.70, 0.87, and $1.0 \text{ Jy beam}^{-1} \text{ km s}^{-1}$, integrated from 1946 to 2259 km s^{-1} . Note the difference in dynamic range of contours for the galaxy and the stream, selected for viewing ease. The $3'$ circle in midstream indicates the position of VIRGOHI 21 reported by Minchin et al. (2005a). The ellipse on the bottom right indicates the size of the Arecibo beam. *Right*: Velocities of the H I emission peaks as seen in LBW pointings. Some of the LBW spectra yielded poor baselines or poor peak definition.

dominant $m = 1$ spiral mode is evident in its conspicuous southwestern spiral arm and the lesser but still prominent arm with several muted branches seen to the north and east. There is no primary distance measurement, but Solanes et al. (2002) give a mean distance modulus of 31.04 ± 0.04 , derived from several applications of the Tully-Fisher relation, placing it very close to the adopted cluster distance but at a projected separation of 1 Mpc from M87. For 35 galaxies with known redshift within a projected separation of NGC 4254 of 300 kpc, the mean heliocentric velocity is 823 km s^{-1} , with a dispersion of 758 km s^{-1} . With a heliocentric velocity of 2404 km s^{-1} (Giovanelli et al. 2007), NGC 4254 is moving at high speed with respect to the cluster and most of its projected neighbors, and is, in fact, the object with the highest radial velocity seen in that portion of the cluster.

Because of its brightness, size, high gas content, and optical asymmetry, NGC 4254 has been the subject of a number of detailed investigations whose principal aim has been to understand the origin of its lopsidedness and strong $m = 1$ spiral mode, particularly in the absence of an appreciable bar or nearby companion. Various studies of the gaseous components have confirmed the strongly asymmetric optical structure. The H α (Phookun et al. 1993; Chemin et al. 2006) and ^{12}CO ($J = 1\text{--}0$) maps are consistent with the picture of an externally forced spiral density wave. Explanations for its asymmetry include the superposition of spiral modes induced by global gravitational instability (Iye et al. 1982), the asymmetric accretion of gas onto the disk (Bournaud et al. 2005), ram pressure stripping (Phookun et al. 1993; Sofue et al. 2003), and a close high-speed encounter plus ram pressure (Vollmer et al. 2005).

In contrast to many spirals found within the inner 1.5 Mpc of Virgo, NGC 4254 appears to have a normal H I content relative to field Sc galaxies of comparable linear size, a healthy H α extent relative to its older R-band stellar population (Koopmann et al. 2006), a relatively normal molecular content (Nak-

anishi et al. 2006), and a typical disk metallicity gradient (Zaritsky et al. 1994). Hence, NGC 4254 appears to have not yet suffered significant gas removal or star formation quenching.

Using VLA H I synthesis mapping, Phookun et al. (1993) first reported the presence of an extra component of H I superposed on the main, rotating disk of NGC 4254. They estimated the H I mass of the disk to be $\sim 4.8 \times 10^9 M_\odot$, with the mass in “high-velocity clouds” $\sim 3\%$ of that number. As seen in their VLA H I map (Fig. 5 of Phookun et al. 1993), the extra gas forms a loop on the northeast side of the galaxy at high velocity, complemented by several lower velocity clouds which form an extended tail on the southwest side. The latter connect to the much longer H I stream seen in the ALFALFA data. This connection is also clearly evident in the top panel of Figure 1 of Vollmer et al. (2005), who reprocessed the original VLA map.

Details of the distortion of the H I layer in a number of galaxies in the Virgo Cluster are seen in an accumulating number of H I maps of Virgo galaxies. The most dramatic evidence of gas compression and stripping is seen in the H I-deficient spirals found close to the cluster center, yet extradisk gas is found in a variety of cases. Oosterloo & van Gorkom (2005) propose that an H I cloud of $3.4 \times 10^8 M_\odot$ and extending some 100×25 kpc has been stripped from the strongly deficient Virgo core spiral NGC 4388 by ram pressure due to the surrounding intracluster medium. Further out from M87, Chung et al. (2007) report several one-sided H I tails pointing away from M87 and suggest they result from ram pressure exerted by the hot intracluster medium.

NGC 4254 is moving at high velocity with respect to the cluster but is located 1 Mpc from M87, where the intracluster medium density is quite low. While Sofue et al. (2003) conclude that the distribution and kinematics of the molecular gas in the inner regions of the galaxy are consistent with the effects of ram pressure as NGC 4254 falls into the Virgo Cluster, Cayatte et al. (1994) suggest that the gravitational restoring force within NGC 4254 probably exceeds the ram pressure force at its current location on the outskirts of the X-ray-emitting region. That ram pressure alone cannot explain the H I and optical asymmetry is further emphasized by Vollmer et al. (2005).

While ram pressure is often invoked to explain lopsidedness, gas compression, and H I deficiency, gravitational rather than hydrodynamical forces may produce similar effects. Of particular relevance are the simulations of galaxy harassment reported by Moore et al. (1996b, 1998). Those authors explored the collective impact of both high-speed encounters and the tidal effects of a smooth cluster potential in a variety of cases, one of which was a spiral galaxy with circular velocity ~ 160 km s⁻¹, nearly identical to that of NGC 4254. The most outstanding characteristics of the H I tail reported here are consistent with the harassment scenario: (1) its clear association with an exceptional galaxy NGC 4254, located 1 Mpc from the center of Virgo and traveling at high speed; (2) its overall length (242 kpc); (3) its modest gas mass ($6 \times 10^8 M_\odot$), about 10% of the total H I associated with NGC 4254; and (4) its roughly sinusoidal velocity field (Fig. 1, *right*). Unlike the strongly deficient case of NGC 4388 (Oosterloo & van Gorkom 2005), NGC 4254 is not H I-poor, so we can conclude it has not passed through the Virgo core in recent epochs. Its distance of 1 Mpc from M87 is not coincidental: the galaxy density there is already quite high, so that a close high-speed encounter is not improbable. A curious aspect of NGC 4254, cited in support of the “dark galaxy” hypothesis for VIRGOHI 21 (Minchin et al. 2005a), is its lack of an obvious close companion

which might be responsible for driving its extraordinary spiral pattern. However, within the framework of the harassment hypothesis, the harassers need not be nearby: the collective cluster potential, as we have seen, is centered 1 Mpc away, and the galaxies with which NGC 4254 may have had a close encounter would rapidly move far away due to their high relative speed. Moore et al. (1996b) further note that such harassment can result in disruption of the inner disk (Moore et al. 1996b) as seen in NGC 4254.

Furthermore, the broad velocity width (~ 220 km s⁻¹) of the section of the NGC 4254 H I tail identified as VIRGOHI 21 by Minchin et al. (2005a, 2005b) also led those authors to argue that the feature must be a massive rotating “dark” galaxy. As Bekki et al. (2005) have shown, gravitational forces are more likely to produce broad velocity widths and large velocity gradients than is ram pressure stripping. The full view of the tail provided by ALFALFA shows the width of VIRGOHI 21 to be not necessarily due to galaxy-scale rotation but rather to a part of a larger scale velocity field.

In the harassment interpretation, the velocity field along the stream suggests a timing argument. We hypothesize that the roughly full cycle, sinusoidal velocity signature apparent in Figure 1 (*right*) reflects the coupling of the spin and tidal motions. Because gas is stripped more readily from that portion of the galaxy whose velocity vector aligns with the direction of the tidal force, we assume that the H I present in the stream was removed from the edge of the outer disk of NGC 4254. The H I diameter derived from the VLA maps is $\sim 7.7'$ (Cayatte et al. 1994; Phookun et al. 1993), yielding an outer radius of 18.5 kpc. Adopting the observed flat rotation curve with a velocity in the outer portions of ~ 150 km s⁻¹ (Guhathakurta et al. 1988; Phookun et al. 1993), the rotation period at a radius of 18.5 kpc corresponds to $\sim 7.5 \times 10^8$ yr, which is comparable to the cluster crossing time. NGC 4254 is not a particularly massive system: the mass enclosed within an 18.5 kpc radius is of order $10^{11} M_\odot$; the Virgo Cluster mass within a 6° radius is estimated to be $(4.0 \pm 1.0) \times 10^{14} M_\odot$ (Hoffman et al. 1980). Thus, tidal forces due to high-speed encounters and/or the collective cluster potential could easily strip the outer gas layers of NGC 4254 in a prograde orbit that passes within 1 Mpc of the cluster center.

Based on the discovery of relatively long stellar streams visible in very deep optical images of Virgo (Mihos et al. 2005), Centaurus, and Coma, Calcáneo-Roldán et al. (2000) and Rudick et al. (2006) have shown that such structures may arise when a relatively luminous spiral galaxy suffers tidal shocking on a prograde encounter deep within the cluster potential. The NGC 4254 event appears to be of a milder nature than those illustrated in those works, presumably because NGC 4254 has not plunged very deep into the cluster core. A stellar stream may be present but would be harder to discern in this case, given the significantly smaller optical light radius of the galaxy and the consequent rarefaction of the stellar density outside 18.5 kpc.

We propose that the most likely interpretation of the galaxy’s asymmetry, its very extended H I tail, and the origin of VIRGOHI 21 is an ongoing process of galaxy harassment, resulting from the high-speed gravitational perturbations experienced by NGC 4254 as it enters the Virgo Cluster.

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REFERENCES

- Bekki, K., Koribalski, B. S., & Kilborn, V. A. 2005, *MNRAS*, 363, L21
- Binggeli, B., Tammann, G. A., & Sandage, A. 1987, *AJ*, 94, 251
- Bournaud, F., Combes, F., Jog, C. J., & Puerari, I. 2005, *A&A*, 438, 507
- Calcáneo-Roldán, C., Moore, B., Bland-Hawthorn, J., Malin, D., & Sadler, E. M. 2000, *MNRAS*, 314, 324
- Cayatte, V., van Gorkom, J. H., Balkowski, C., & Kotanyi, C. 1990, *AJ*, 100, 604
- . 1994, *AJ*, 107, 1003
- Chamaraux, P., Balkowski, C., & Gerard, E. 1980, *A&A*, 83, 38
- Chemin, L., et al. 2006, *MNRAS*, 366, 812
- Chung, A., van Gorkom, J. H., Kenney, J. D. P., & Vollmer, B. 2007, *ApJ*, 659, L115
- Davies, J., et al. 2004, *MNRAS*, 349, 922
- Davies, R. D., & Lewis, B. M. 1973, *MNRAS*, 165, 231
- Giovanelli, R., & Haynes, M. P. 1983, *AJ*, 88, 881
- Giovanelli, R., et al. 2005, *AJ*, 130, 2598
- . 2007, *AJ*, 133, 2569
- Guhathakurta, P., van Gorkom, J. H., Kotanyi, C. G., & Balkowski, C. 1988, *AJ*, 96, 851
- Hoffman, G. L., Olson, D. W., & Salpeter, E. E. 1980, *ApJ*, 242, 861
- Iye, M., et al. 1982, *ApJ*, 256, 103
- Kent, B. R., et al. 2007, *ApJ*, 665, L15
- Koopmann, R. A., Haynes, M. P., & Catinella, B. 2006, *AJ*, 131, 716
- Mei, S., et al. 2007, *ApJ*, 655, 144
- Mihos, J. C., Harding, P., Feldmeier, J., & Morrison, H. 2005, *ApJ*, 631, L41
- Minchin, R., et al. 2005a, *ApJ*, 622, L21
- . 2005b, preprint (astro-ph/0508153)
- Moore, B., Katz, N., & Lake, G. 1996a, *ApJ*, 457, 455
- Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A., Jr. 1996b, *Nature*, 379, 613
- Moore, B., Lake, G., & Katz, N. 1998, *ApJ*, 495, 139
- Nakanishi, H., et al. 2006, *ApJ*, 651, 804
- Oosterloo, T., & van Gorkom, J. 2005, *A&A*, 437, L19
- Phookun, B., Vogel, S. N., & Mundy, L. E. 1993, *ApJ*, 418, 113
- Rudick, C. S., Mihos, J. C., & McBride, C. 2006, *ApJ*, 648, 936
- Saintonge, A. 2007, *AJ*, 133, 2087
- Sofue, Y., Koda, J., Nakanishi, H., & Hidaka, M. 2003, *PASJ*, 55, 75
- Solanes, J. M., Sanchis, T., Salvador-Solé, E., Giovanelli, R., & Haynes, M. P. 2002, *AJ*, 124, 2440
- Vollmer, B., Huchtmeier, W., & van Driel, 2005, *A&A*, 439, 921
- Zaritsky, D., Kennicutt, R. C., Jr., & Huchra, J. P. 1994, *ApJ*, 420, 87

Note added in proof.—We have recently learned that P.-A. Duc & F. Bournaud (2007, *ApJ*, submitted) have modeled the formation of a tidal tail in NGC 4254, with the characteristics described in this work, resulting from a very high speed encounter with another cluster galaxy now far removed from NGC 4254.