DRAFT VERSION JULY 3, 2007
Preprint typeset using LATEX style emulateapj v. 10/10/03

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

MARTHA P. HAYNES[1,2], RICCARDO GIOVANELLI[1,2], AND BRIAN R. KENT[1]

Draft version July 3, 2007

ABSTRACT

We present an HI 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 HI 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 HI tail extending ~ 250 kpc northward from the galaxy. Embedded as one condensation within this HI structure is the object previously identified as a "dark galaxy": Virgo HI21 (Davies *et al.* 2004). 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, extra-disk HI and lengthy HI tail is consistent with a picture of "galaxy harassment" as proposed by Moore *et al.* (1996a,b; 1998). 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: intergalactic medium — galaxies: halos — individual: Virgo cluster — radio lines: HI — galaxies: clusters — galaxies: interactions

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 HI deficiency first quantified the impact of the cluster environment (Davies & Lewis 1973; Chamaraux, Balkowski & Gerard 1980), while subsequent mapping of the gas distribution proved that the HI disks of the highly gas-poor objects were systematically smaller than those of galaxies of normal HI content (Giovanelli & Haynes 1983; Cayatte *et al.* 1990). Further HI synthesis observations, most recently those of the VLA Imaging of Virgo Galaxies (VIVA) Survey (Chung *et al.* 2007), yield details of the HI distribution in a growing selection of Virgo galaxies. Concurrently, the Arecibo Legacy Fast ALFA (ALFALFA) survey is conducting a sensitive blind HI survey of the entire Virgo cluster region, identifying a host of HI features that are not coincident with stellar counterparts (Kent *et al.* 2007). The combined picture provided by both the blind and targeted HI 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 NW of M87. Binggeli *et al.* (1985) assigned it membership in the main Virgo A cluster, so that 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 ~ 1300 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 2.2×10^8 $M_\odot$ of HI at a position some 120 kpc north of NGC 4254. HI emission was detected in a total of five adjacent Arecibo pointings, spaced at intervals of 2.7′, and centered on (α, δ, J2000) $12^h17^m53.6^s$, $+14°45'25''$. Based on the Arecibo observations, especially the relatively broad HI line width of 220 km s^{-1}, and the lack of detectable HI in a VLA synthesis map, they argued that Virgo HI21 is the disk of a large (>16 kpc in diameter), optically–dark galaxy with a much larger total mass than that of the HI itself (Minchin *et al.* 2005b). They noted that Virgo HI21 lies about 120 kpc from both NGC 4262 and NGC 4254 but argued against any tidal connection with either, both because of the relatively large separation and their high relative velocity.

In this Letter, we exploit the wide field HI maps of the ALFALFA survey to detail a long complex of HI clouds, extending from NGC 4254 northward. Virgo HI21 is shown to be one condensation within this HI tail. Deeper observations subsequently undertaken at Arecibo allow us to trace the HI to a distance of ~ 250 kpc to the north of NGC 4254. In section 2 we describe the ALFALFA data and followup Arecibo observations. In section 3, we discuss the body of evidence regarding NGC 4254 in terms of the galaxy harassment scenario of Moore *et al.* (1996a,b; 1998). All coordinates are for epoch J2000.0.

[1] Center for Radiophysics and Space Research, Space Sciences Building, Cornell University, Ithaca, NY 14853. *e–mail:*haynes@astro.cornell.edu, riccardo@astro.cornell.edu, bkent@astro.cornell.edu
[2] National Astronomy and Ionosphere Center, Cornell University, 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.

2. OBSERVATIONS AND ANALYSIS

The region around NGC 4254 and Virgo HI21 has been mapped as part of the ALFALFA survey program. ALFALFA is a two-pass survey which uses the 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, 3-D spectral line data cubes are constructed and a signal extraction algorithm, discussed in Saintonge (2007), is applied for preliminary identification of HI sources. HI sources in the northern part of Virgo were included in the first ALFALFA catalog release (Giovanelli *et al.* 2007), covering between $+12° < \delta < +16°$. That tabulation includes 17 HI detections within 1° of Virgo HI21 ($\alpha = 12^h18^m$, $\delta = +14°44'$) and at velocities $cz < 3000$ km s^{-1}. Of the 17 HI 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–Virgo HI21 system, while the remaining one is probably a foreground Milky Way high velocity cloud.

The left panel of Figure 1 shows the integrated HI flux density contours as detected in the ALFALFA data set overlayed on the 2nd generation Digital Sky Survey Blue image in the vicinity north of NGC 4254. The HI emission is integrated over the range cz = 1946 to 2259 km s^{-1} for the stream and cz = 2259 to 2621 for the galaxy on a grid with $1'$ spacing. The velocity cut for the stream is outside the 2250-2510 km s^{-1} range reported in VLA maps of NGC 4254 (Vollmer *et al.* 2005). The superposed circle at $\alpha = 12^h17^m53.6^s$, $\delta = +14°45'25''$ indicates the centroid of Virgo HI21 as reported by Minchin *et al.* (2005a). HI 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, explore the velocity field along it, a set of HI spectra were obtained along the ridge of the HI 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 spectral resolution of 12.2 kHz (2.6 km s^{-1} at cz = 2000 km s^{-1}). The integration times varied from three to six minutes on source, depending on the expected signal strength, yielding an rms noise per channel of better than ~2.6 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 dots superposed along the peak of the stream illustrated in the left panel of Figure 1. The peak velocity at each pointing for which the detected signal is significant is indicated on the position-velocity diagram in the right hand inset. 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 HI mass for NGC 4254 itself of $4.3 \times 10^9\ M_\odot$. The total HI 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 $M_{HI} \sim 4.3 \times 10^8\ M_\odot$. 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 3×10^{18} HI atoms cm^{-2} over a solid angle of 200 (arcmin)^2, up to an additional $1.1 \times 10^8\ M_\odot$ of HI may be present in the stream, bringing the total HI mass to $5.0 \pm 0.6 \times 10^8\ M_\odot$. The HI 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 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 Hα (Phookun, Vogel & Mundy 1993; Chemin *et al.* 2006) and ^{12}CO(J=1-0) 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, Vogel & Mundy 1993; Sofue *et al.* 2003) and a close high speed encounter plus ram pressure (Vollmer, Huchtmeier & van Driel 2005).

In contrast to many spirals found within the inner 1.5 Mpc of Virgo, NGC 4254 appears to have a normal HI content relative to field Sc's of comparable linear size, a healthy Hα extent relative to its older R-band stellar population (Koopmann, Haynes & Catinella 2006), a relatively normal molecular content (Nakanishi *et al.* 2006), and a typical disk metallicity gradient(Zaritsky *et al.* 1994). Hence, NGC 4254 appears not to have yet suffered significant gas removal or star formation quenching.

Using VLA HI synthesis mapping, Phookun, Vogel & Mundy (1993) first reported the presence of an extra component of HI superposed on the main, rotating disk of NGC 4254. They estimated the HI 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 HI map (Figure 5 of Phookun, Vogel & Mundy 1993), the extra gas forms a loop on the NE side of the galaxy at high velocity, complemented by several lower velocity clouds which form an extended tail on the SW side. The latter connect to the much longer HI stream seen in the ALFALFA data. This connection is also clearly evident in the top panel of Figure 1 of Vollmer, Huchtmeier & van Driel (2005) who reprocessed the original VLA map.

Details of the distortion of the HI layer in a number of galaxies in the Virgo cluster are seen in an accumulating number of HI maps of Virgo galaxies. The most dramatic evidence of gas compression and stripping is seen in the HI deficient spirals found close to the cluster center, yet extra-disk gas is found in a variety of cases. Oosterloo & van Gorkom (2005) propose that an HI cloud of $3.4 \times 10^8\ M_\odot$ and extending some 100 by 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 HI 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 HI and optical asymmetry is further emphasized by Vollmer, Huchtmeier & van Driel (2005).

While ram pressure is often invoked to explain lopsidedness, gas compression and HI deficiency, gravitational rather than hydrodynamical forces may produce similar effects. Of particular relevance are the simulations of galaxy harassment reported by Moore *et al.* (1996a) and Moore, Lake & Katz (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 $\sim$160 km s^{-1}, nearly identical to that of NGC 4254. The most outstanding characteristics of the HI tail reported here are consistent with the harassment scenario: (a) its clear association with an exceptional galaxy NGC 4254, located 1 Mpc from the center of Virgo and traveling at high speed; (b) its overall length (242 kpc); (c) its modest gas mass ($6 \times 10^8\ M_\odot$), about 10% of the total HI associated with NGC 4254; and (d) its roughly sinusoidal velocity field (right panel of Figure 1). Unlike the strongly deficient case of NGC 4388 (Oosterloo & van Gorkom 2005), NGC 4254 is not HI poor, so that 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 Virgo HI21 (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.* (1996a) further note that such harassment can result in disruption of the inner disk (Moore *et al.* 1996a) as seen in NGC 4254.

Furthermore, the broad velocity width (~ 220 km s^{-1}) of the section of the NGC 4254 HI tail identified as Virgo HI21 by Minchin *et al.* (2005a,b) also led those authors to argue that the feature must be a massive rotating "dark" galaxy. As Bekki, Koribalski & Kilborn (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 Virgo HI21 to be not necessarily due to galaxy–scale rotation, but rather 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 the right panel of Figure 1 reflects the coupling of the spin and tidal motions. Because gas is stripped more readily from that portion of the galaxy whose rotation aligns with the direction of the tidal force, we assume that the HI present in the stream was removed from the edge of the outer disk of NGC 4254. The HI diameter derived from the VLA maps is $\sim 7.7'$ (Cayatte *et al.* 1994; Phookun, Vogel & Mundy 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, Vogel & Mundy 1993), the rotation period at a radius of 18.5 kpc corresponds to $\sim 7.5 \times 10^8$ years, which is comparable with 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, Olson & Salpeter 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, Mihos & McBride (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 HI tail and the origin of Virgo HI21 is an on-going process of galaxy harassment, resulting from the high speed gravitational perturbations experienced by NGC 4254 as it enters the Virgo cluster.

Note added in proof: We have recently learned that Bournaud & Duc (2007, in preparation) 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.

RG and MPH acknowledge the partial support of NAIC as Visiting Scientists during the period of this work. This work has been supported by NSF grants AST–0307661, AST–0435697, AST–0347929, AST–0407011, AST–0302049; and by a Brinson Foundation grant.

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

Cayatte, V., van Gorkom, J.H., Balkowski, C., & Kotanyi, C. 1994, AJ, 107, 1003

Chamaraux, P., Balkowski & Gerard, E. A&A, 83, 38

Chemin, L., Balkowski, C., Cayatte, V., Carignan, C., Amram, P., Garrido, O., Hernandez, O., Marcelin, M., Adami, C., Boselli, A. & Boulesteix, J. 2006, MNRAS, 366, 812

Chung, A., van Gorkom, J.H., Kenney, J.D.P., & Vollmer, B. 2007, ApJ, 659, 115

Davies, R.D. & Lewis, B.M. 1973, MNRAS, 165, 231

Davies, J., Minchin, R., Sabatini, S., van Driel, W., Baes, M. *et al.* 2004, MNRAS, 349, 922

Giovanelli, R. & Haynes, M.P. 1983, AJ, 88, 881

Giovanelli, R., Haynes, M.P., Kent, B.R. *et al.* 2005, AJ, 130, 2598

Giovanelli, R., Haynes, M. P., Kent, B. R. *et al.* 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

Kent, B.R., Giovanelli, R., Haynes, M.P., *et al.* 2007, ApJ, in press

Koopmann, R.A., Haynes, M.P. & Catinella, B. 2007, AJ, 131, 716

Mei, S., Blakeslee, J.P., Côté, P., Tonry, J.L., West, M.J. *et al.* 2007, ApJ655, 144

Mihos, J.C., Harding, P., Feldmeier, J. & Morrison, H. 2005, ApJ, 631, L41

Minchin, R., Davies, J., Disney, M., Boyce, P., Garcia, D. *et al.* 2005a, ApJ, 622, L21

Minchin, R.F., Davies, J.I., Disney, M.J., Marble, A. R., Impey, C. D., *et al.* 2005b, astro-ph/0508153

Moore, B., Katz, N., Lake, G., Dressler, A. & Oemler, A., Jr. 1996a, Nature, 379, 613

Moore, B., Katz, N. & Lake, G. 1996b, ApJ, 457, 455

Moore, B., Lake, G. & Katz, N. 1998, ApJ, 495, 139

Nakanishi, H., Kuno, N., Sofue, Y., Sato, N., Nakai, N. *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

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

Springob, C.M., Haynes, M.P., Giovanelli, R. & Kent, B.R. 2005, ApJS, 160, 149

Vollmer, B., Huchtmeier, W., & van Driel, 2005, A&A, 439, 921

Zaritsky, D., Kennicutt, R.C., Jr. & Huchra, J.P. 1994, ApJ, 420, 87

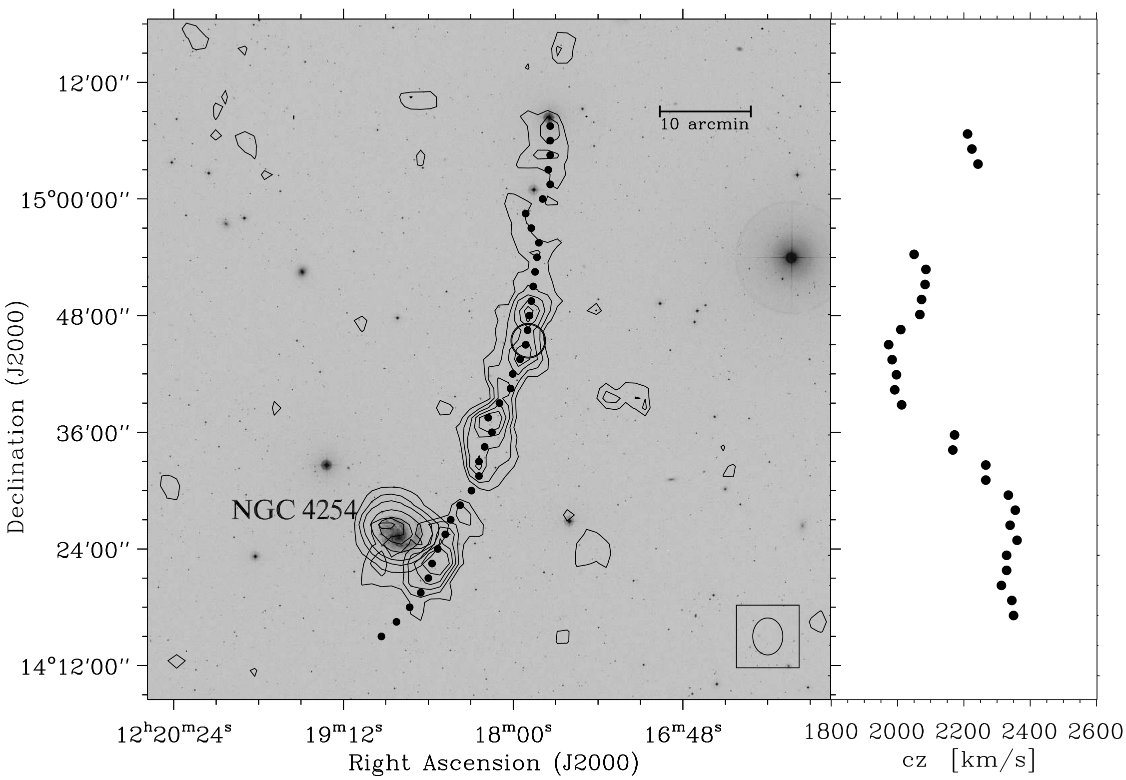

Fig. 1.— Left: HI flux contours extracted from the ALFALFA survey dataset, which mapped the full field represented in the image, superposed on a DSS2 Blue image. The 36 filled dots indicate the locations of beam centers for the successive LBW observations. The contours centered on NGC 4254 are at 10, 15, 20, 30, and 40 Jy beam^{-1} km s^{-1}, integrated from 2259 to 2621 km s^{-1}. The contours for the HI stream are at 0.35, 0.52, 0.70, 0.87, and 1.0 Jy beam^{-1} 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 mid stream indicates the position of Virgo HI21 reported by Minchin *et al.*(2005a). The ellipse on the bottom right indicates the size of the Arecibo beam. Right: The velocity of the HI emission peak as seen in LBW pointings. Some of the LBW spectra yielded poor baselines or poor peak definition.