

A DARK HYDROGEN CLOUD IN THE VIRGO CLUSTER

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ABSTRACT

VIRGOHI 21 is an H I source detected in the Virgo Cluster survey of Davies et al. that has a neutral hydrogen mass of $10^8 M_\odot$ and a velocity width of $\Delta V_{20} = 220 \text{ km s}^{-1}$. From the Tully-Fisher relation, a galaxy with this velocity width would be expected to be 12 mag or brighter; however, deep CCD imaging has failed to turn up a counterpart down to a surface brightness level of 27.5 *B* mag arcsec⁻². The H I observations show that it is extended over at least 16 kpc, which, if the system is bound, gives it a minimum dynamical mass of $\sim 10^{11} M_\odot$ and a mass-to-light ratio of $M_{\text{dyn}}/L_B > 500 M_\odot/L_\odot$. If it is tidal debris, then the putative parents have vanished; the remaining viable explanation is that VIRGOHI 21 is a dark halo that does not contain the expected bright galaxy. This object was found because of the low column density limit of our survey, a limit much lower than that achieved by all sky H I surveys such as those carried out at Parkes and Jodrell Bank. Further such sensitive surveys might turn up a significant number of the dark matter halos predicted by galaxy formation models.

Subject headings: dark matter — galaxies: clusters: individual (Virgo) — galaxies: general — radio lines: galaxies

1. INTRODUCTION

Simulations of cold dark matter models predict far more dark matter halos than are observed as galaxies (Klypin et al. 1999; Moore et al. 1999). For this reason, it has been hypothesized that there must exist dark matter halos that contain no stars (e.g., Jimenez et al. 1997; Verde et al. 2002). The advent of neutral hydrogen multibeam systems has allowed surveys of large areas of sky to be carried out with much higher sensitivity than has been possible in the past, thus allowing sources to be detected by their gas content alone rather than their stars and opening up the possibility of finding truly isolated clouds of extragalactic gas with no stars. Prior to this, blind H I surveys either covered very small areas or were insensitive to H I column densities lower than $\sim 10^{20} \text{ cm}^{-2}$ ($\sim 1 M_\odot \text{ pc}^{-2}$; Minchin et al. 2003).

Davies et al. (2004) used the multibeam system on the Lovell telescope at Jodrell Bank Observatory to carry out a deep neutral hydrogen (H I) survey of the Virgo Cluster (VIRGOHI), covering 32 deg² and detecting 31 sources. Of these sources, 27 were known cluster members, and four were new detections. One of the latter lies behind M86 and was thus unobservable optically, and one was undetected in follow-up observations and is therefore believed to be a false detection. The other two were confirmed at Arecibo and flagged by Davies et al. as possible isolated H I clouds. One (VIRGOHI 27) has an optical

counterpart visible in our deep CCD images; the other (VIRGOHI 21, the subject of this Letter) does not.

There have been several previous claims of the detection of isolated clouds of extragalactic gas with no stars in them, but subsequent analyses have either revealed the optical counterparts (Giovanelli & Haynes 1989; McMahon et al. 1990) or shown that the gas is merely debris from nearby visible galaxies (Schneider et al. 1983; Schneider 1989). Many other detections of H I clouds have been associated with nearby optically bright galaxies (Kilborn et al. 2000; Boyce et al. 2001; Ryder et al. 2001). VIRGOHI 21 cannot be so easily explained.

2. FURTHER OBSERVATIONS

Following detection, VIRGOHI 21 was reobserved at Arecibo. The observations are fully described by Davies et al. (2004); here we give a much more detailed analysis of the Arecibo data and present new Very Large Array (VLA) and optical observations. The Arecibo observations used a number of pointings in a pattern around the best-fit location from the Jodrell Bank data, leading to the source being detected in five of the Arecibo beams.

Figure 1 shows the single-dish spectra of VIRGOHI 21. Spectrum *a* is the discovery spectrum from Jodrell Bank; this has a noise level of 4 mJy per 13.2 km s⁻¹ channel and a 5 σ column density sensitivity $N_{\text{H I, lim}} = 7 \times 10^{18} \text{ cm}^{-2}$ if spread over 200 km s⁻¹. From it we measure a total flux of $F_{\text{H I}} = 2.4 \pm 0.3 \text{ Jy km s}^{-1}$ and a velocity width at 20% of the peak flux of $\Delta V_{20} = 290 \text{ km s}^{-1}$. Spectra *b*, *c*, and *d* are three north through south beams across the source from the Arecibo observations (labeled *b–d* in Fig. 2). These have a noise level of 1.3 mJy per 5.5 km s⁻¹ channel, giving $N_{\text{H I, lim}} = 2.7 \times 10^{19} \text{ cm}^{-2}$ over 200 km s⁻¹. They reveal a systematic increase in velocity of $\sim 200 \text{ km s}^{-1}$ from south to north. Spectrum *e* is the co-added spectrum from all 16 Arecibo beams (shown in Fig. 2) from which we measure $F_{\text{H I}} = 3.8 \pm 0.2 \text{ Jy km s}^{-1}$ and $\Delta V_{20} = 220 \text{ km s}^{-1}$.

Figure 2 shows the Arecibo pointing pattern for VIRGOHI 21 and which beams made firm detections (better than 4 σ). It can be seen that VIRGOHI 21 is extended over at least one Arecibo beamwidth $\approx 3'.6$, or 16 kpc at an assumed distance to Virgo of 16 Mpc (Graham et al. 1999). Using the Arecibo

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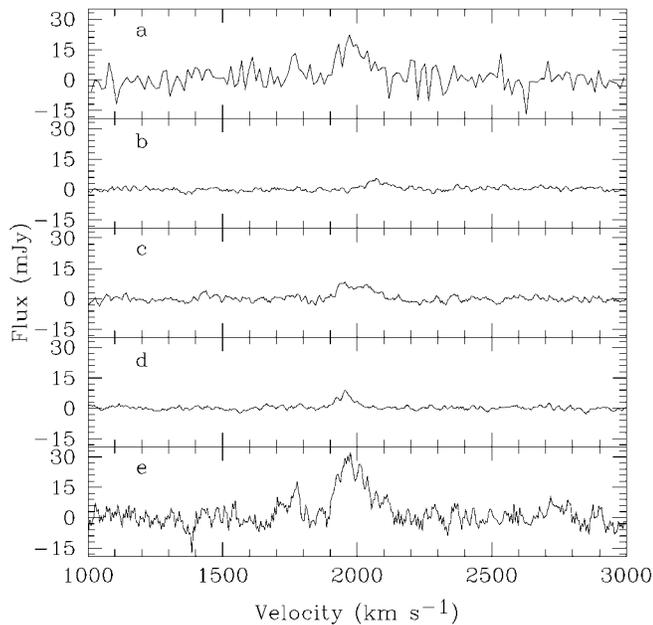


FIG. 1.—Atomic hydrogen spectra of VIRGOHI 21 plotted as a function of recessional velocity. (a) Discovery spectrum from Jodrell Bank (3500 s). (b–d) Arecibo follow-up spectra from beams labeled b–d in Fig. 2, cutting north-south across the source (600 s). (e) Sum of all Arecibo spectra (600 s beam⁻¹). The peak at ~1750 km s⁻¹ in spectrum e can be clearly associated with galaxy C in Fig. 3 by our VLA data.

H I flux, we calculate an H I mass of $2 \times 10^8 M_{\odot}$ if it is at the distance of the Virgo Cluster or $7 \times 10^8 M_{\odot}$ if it is at its Hubble distance (29 Mpc for $H_0 = 70 \text{ Mpc}^{-1} \text{ km s}^{-1}$). For the rest of this Letter we will assume the former as more conservative in this context. The best position for the center of the H I emission, formed by weighting the Arecibo detection positions by their fluxes, is $12^{\text{h}}17^{\text{m}}53^{\text{s}}.6$, $+14^{\circ}45'25''$ (J2000). We can dismiss the possibility that this is sidelobe emission from another part of the sky, because VIRGOHI 21 has been detected with two telescopes with very different sidelobes. Additionally, there are no H I massive galaxies in the region that match its velocity profile (Davies et al. 2004).

H I observations with the VLA in D array in 2004 August reached a 5σ column density limit of 10^{20} cm^{-2} over 60 km s⁻¹ in 6 hr (0.5 mJy per 20 km s⁻¹ channel with a beam size of $48'' \times 45''$ using natural weighting). Solar interference on the shorter baselines meant that the observations did not reach the hoped for column density sensitivity; most of the data from baselines shorter than ~270 m (~1.3 kλ) had to be flagged as bad. These observations did detect compact H I associated with a nearby dwarf elliptical galaxy (MAPS-NGP O-435-1291894) at a different velocity but, although sensitive to compact, narrow-line gas down to a 5σ limit of $3 \times 10^6 M_{\odot}$, were not sensitive enough to low column density, high-velocity width gas to detect VIRGOHI 21. For the Arecibo and VLA observations to be consistent, the source must again exceed 16 kpc in diameter.

We have obtained deep optical CCD images in *B*, *r*, and *i* bands with the 2.5 m Isaac Newton Telescope (INT). By binning the *B*-band image (generally the best band for looking for low surface brightness galaxies) into $1''$ pixels, we reach a surface brightness limit of $27.5 B \text{ mag arcsec}^{-2}$; treating the *r* and *i* images in the same way gives surface brightness limits of ~27.0 and of $25.8 \text{ mag arcsec}^{-2}$, respectively. Previous experience indicates that, on the *B*-band frame, we should be able

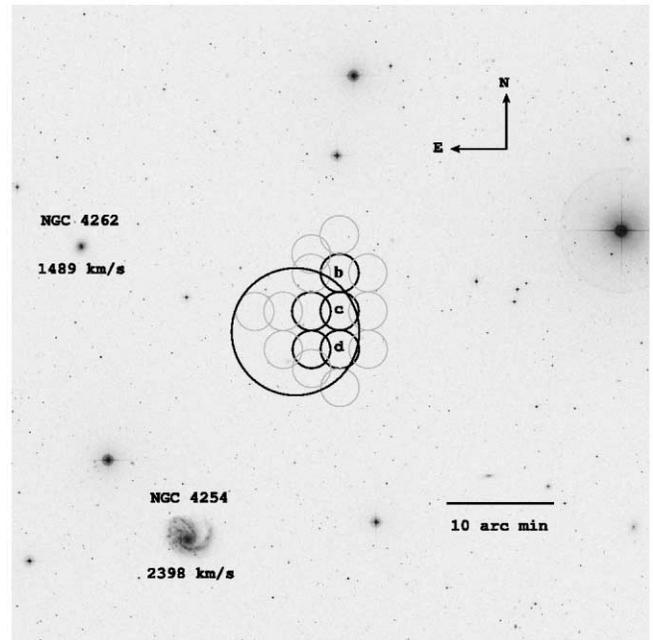


FIG. 2.—Arecibo pointing pattern for VIRGOHI 21 overlaid on a digitized sky survey image of the region around the source. Circles mark the beam position and FWHM; black circles denote beams where a firm detection (better than 4σ) was made, and gray circles those beams that do not contain a definite signal. The large circle marks the beam corresponding to the pixel in the Jodrell Bank data cube from which the spectrum and measurements in Fig. 1a are taken. The beams marked b, c, and d correspond to the spectra marked b, c, and d in Fig. 1.

to easily detect objects of $10''$ scale or larger at this surface brightness limit (Sabatini et al. 2003; Roberts et al. 2004). This is more than 100 times dimmer than the central surface brightness of the disks of typical spiral galaxies ($21.5 B \text{ mag arcsec}^{-2}$; Freeman 1970) and dimmer than any known massive low surface brightness galaxy ($26.5 B \text{ mag arcsec}^{-2}$; Bothun et al. 1987) or (for typical $B - V$ colors of ~0.6) than the lowest surface brightness dwarf galaxy ($26.8 V \text{ mag arcsec}^{-2}$; Zucker et al. 2004).

Although we easily were able to identify an optical counterpart (at $12^{\text{h}}26^{\text{m}}40^{\text{s}}.1$, $+19^{\circ}45'50''$ [J2000]) to the other possible H I cloud, VIRGOHI 27, no optical counterpart to VIRGOHI 21 is visible down to our surface brightness limit on any of our deep images of this region (Fig. 3), nor can one be found with advanced routines for detecting low surface brightness galaxies (matched filtering and wavelets; Sabatini et al. 2003). Unlike VIRGOHI 27, the bluest objects in the field, which might be associated with H II regions, are widely distributed without any concentration toward the H I center. Looking at the statistics of the sky noise for the frame, the mean number of counts and the standard deviation (excluding stars) are similar in the area of the H I detection to other, blank areas of sky in the vicinity. The number of detected faint objects is not significantly above the average in a box centered on the H I position: there are three objects with $m_B > 23$ in a 100×100 pixel ($33''.3 \times 33''.3$) region centered on our best H I position, compared to an average of 1.8 ± 1.4 across the cube, and four objects with $m_B > 22$, compared to an average of 2.6 ± 1.7 .

As is to be expected there are some features on the image of VIRGOHI 21 that are obviously faint galaxies. These are labeled A–E in Figure 3. “A” is a small source with a star superposed (which prevents us from making an accurate de-

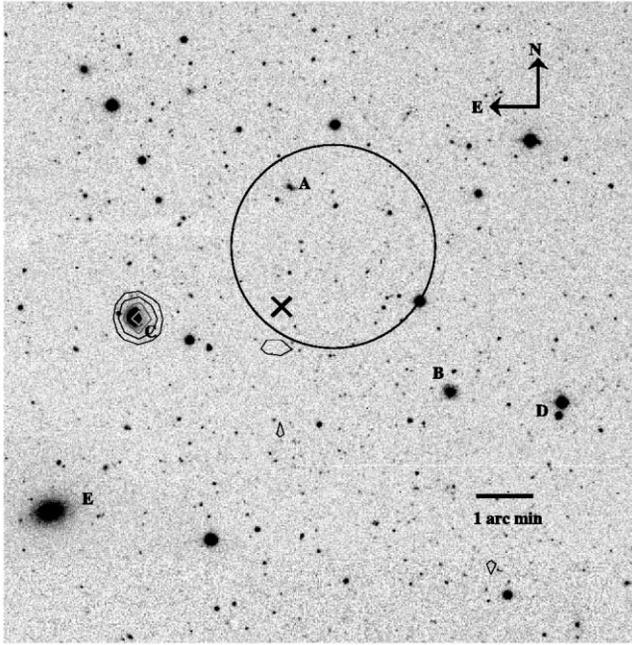


FIG. 3.—INT *B*-band optical image (shown as negative) of the field of VIRGOHI 21. The cross marks the weighted center of the H I detection, and the circle shows the size and position of the central Arecibo beam. Optical sources labeled A–E are discussed in the text. Contours show the moment map from the VLA detection of source C ($M_{\text{H I}} = 1.4 \times 10^7 M_{\odot}$) at 1750 km s^{-1} and are at 3, 6, 9, and 12σ .

termination of its color and luminosity) $2'$ north of the weighted center, just within the FWHM of the strongest H I beam. Its east-west orientation is at odds with the north-south orientation expected from the velocity field of VIRGOHI 21, and, if VIRGOHI 21 is rotating, this galaxy is too far north for the rotation to be centered on its position. Neither its size, position, nor orientation make this a likely optical counterpart to VIRGOHI 21. “B” is another uncataloged galaxy, $3.5'$ southwest of the weighted center. It lies within the FWHM of an Arecibo beam where there was no detection; thus, it cannot be the optical counterpart. There are three objects classified as galaxies within $6'$. One (C) at the very edge of one of the Arecibo beams is a dwarf galaxy (MAPS-NGP O-435-1291894) that is detected in our VLA data at 1750 km s^{-1} (see Fig. 1). The H I is separated both spatially and in velocity from VIRGOHI 21, and so therefore it cannot be the optical counterpart. Another of the cataloged galaxies (D: MAPS-NGP O-435-1292289) is a double star miscataloged as a galaxy, and the third (E: VCC 0273) lies in an Arecibo beam where no detection was made.

We conclude that there is no optical counterpart to VIRGOHI 21 down to a *B*-band surface brightness limit of $27.5 B \text{ mag arcsec}^{-2}$. This is less than $1 L_{\odot} \text{ pc}^{-2}$, giving a maximum luminosity in stars of $\sim 10^8 L_{\odot}$ if a diameter of 16 kpc is assumed. If VIRGOHI 21 is a bound system (see § 3), this leads to a mass-to-light ratio in solar units of $M_{\text{dyn}}/L_B > 500$ compared to a typical L^* galaxy like the Milky Way with $M_{\text{dyn}}/L_B \sim 50$ within its H I radius (Salucci & Persic 1997). For standard stellar M/L_B ratios the upper limit on the mass in stars is approximately equal to the mass in H I.

3. DISCUSSION

The closest bright H I-rich galaxies ($M_B < -16$, $M_{\text{H I}} > 10^8 M_{\odot}$) are shown in Figure 2. These are NGC 4262 at 1489

km s^{-1} and NGC 4254 at 2398 km s^{-1} , each at projected distances of 120 kpc away to the east and southeast, respectively. The nearest H I-rich galaxy within 200 km s^{-1} is NGC 4192A at a projected distance of 290 kpc (Davies et al. 2004). If our detection were tidal debris, then it would have to have been drawn out on a timescale of 16 kpc per 200 km s^{-1} (200 km s^{-1} being the typical velocity width within a single Arecibo beam), or $6 \times 10^7 \text{ yr}$. It follows that the interacting galaxies that generated it must still be close enough that they could have been near VIRGOHI 21 $6 \times 10^7 \text{ yr}$ ago. For the two apparently nearest galaxies (above), that would imply relative projected speeds of greater than 1500 km s^{-1} . This is very high compared to the velocities of galaxies in the outskirts of Virgo (velocity dispersion $\sim 700 \text{ km s}^{-1}$), where VIRGOHI 21 appears to be situated (Davies et al. 2004), and far too high to favor significant tidal interactions (e.g., Toomre & Toomre 1972; Barnes & Hernquist 1992). Furthermore, the observations of VIRGOHI 21 show higher velocities to the north and lower velocities to the south, while the two nearby galaxies are placed with one at a higher velocity to the south and one with a lower velocity slightly north of due east—the opposite sense to that expected if the velocity gradient in VIRGOHI 21 were due to a tidal interaction between them.

If a tidal origin is thus excluded, what alternative explanations are compatible with the wide velocity width? Several narrow-line higher column density clouds at different velocities lined up in the beam? Clouds like this are often associated with tidal debris as the filamentary structure breaks up into separate H I clouds that may form tidal dwarf galaxies (e.g., Hunsberger et al. 1996). Such clouds should have been detected by our VLA observations; that they were not implies that this is an unlikely explanation. Another possibility is that the gas is not bound, but then it should have dispersed in the same short timescale of $6 \times 10^7 \text{ yr}$. Given the dynamical timescale of the cluster of $\sim 10^9 \text{ yr}$, this possibility seems unlikely. The Galactic extinction at this point in the sky is only 0.15 mag in the *B* band (Schlegel et al. 1998); therefore, it is very unlikely that a galaxy has been hidden by obscuration. As the other possibilities seem so unlikely, one is left with the hypothesis that the gas in VIRGOHI 21 is gravitationally bound and moving in stable, bound orbits that prevent shocking—rotation of course comes to mind, as in a flattened disk—a model that is not inconsistent with the spectra. If the system is bound, then its dynamical mass $M_{\text{dyn}} \equiv R_{\text{H I}} \Delta V^2 / G$ is greater than $9 \times 10^{10} M_{\odot}$ (with $R_{\text{H I}} \geq 8 \text{ kpc}$ and $\Delta V = 220 \text{ km s}^{-1}$), not atypical of a rotating galaxy, although its $M_{\text{dyn}}/M_{\text{H I}} > 400$ is about 5 times higher than normal spiral galaxies.

From the well-known Tully-Fisher correlation between rotational velocity and luminosity, calibrated in the Virgo Cluster by Fouqué et al. (1990), our H I detection, if indeed it is a bound system, should correspond to a galaxy with an absolute *B* magnitude of -19 . At the distance of the Virgo Cluster this would correspond to a 12th magnitude galaxy, which would normally be extremely prominent at optical wavelengths. VIRGOHI 21 appears to be a massive object that does not contain the expected bright galaxy.

It has been proposed that there is an H I column density threshold ($\sim 10^{20} \text{ cm}^{-2}$) below which star formation ceases to occur (Toomre 1964; Martin & Kennicutt 2001). The mean column density across our central beam at Arecibo is somewhat lower than this, at $4 \times 10^{19} \text{ cm}^{-2}$, and our VLA observations set an upper limit to the column density of 10^{20} cm^{-2} . This low column density provides an explanation for the lack of an optical counterpart: this may be a dark galaxy that has failed to form stars because the low disk surface density prevents frag-

mentation of the gas; i.e., it does not satisfy Toomre's criterion (Verde et al. 2002; Toomre 1964).

If such dark objects exist in significant numbers, then why has it taken until now to detect one? VIRGOHI 21-like objects could only have been detected by H I surveys that meet three criteria: (1) that they are “blind,” rather than targeted at previously identified objects (which, by definition, are not “dark”); (2) that they have 5σ column density sensitivity to galaxies with velocity widths $\sim 200 \text{ km s}^{-1}$ at the $5 \times 10^{19} \text{ cm}^{-2}$ level (which rules out older H I surveys); and (3) that they have complete optical follow-up observations to deep isophotal limits. While there have been many blind surveys, the only ones to meet the second criterion are the H I Parkes All-Sky Survey (HIPASS; Meyer et al. 2004), the H I Jodrell All Sky Survey (HIJASS; Lang et al. 2003), the Arecibo H I Strip Survey (AHISS; Zwaan et al. 1997), the extragalactic blind survey for very low column density neutral hydrogen (HIDEEP; Minchin et al. 2003), and VIRGOHI (Davies et al. 2004), and of these, only the last three satisfy the third criterion—that they have complete optical follow-up data. The HIPASS Bright Galaxy Catalog (with a peak flux limit of 116 mJy; Koribalski et al. 2004), which has recently been used to make the most accurate determination to date of the H I mass function (Zwaan et al. 2003), would not have detected VIRGOHI 21 unless it were within 6 Mpc—a relatively small distance and very close to the level where it would be impossible, in velocity space, to distinguish a truly isolated H I cloud from one associated with the Galaxy. Taking the volume in which VIRGOHI 21 would have been detected (in HIDEEP, VIRGOHI, and AHISS) leads to a global density of $\sim 0.02 \text{ Mpc}^{-3}$, equivalent to a contribution to the cosmic density of $\Omega \approx 0.01$. To have had more than one detection would therefore imply a very significant contribution to the cosmic density.

4. CONCLUSIONS

In the very nature of things it would be difficult to make an indisputable claim to have found a dark galaxy, particularly when past claims to that effect have quickly been ruled out by subsequent observations (either of a dim underlying galaxy or of bridging connections to nearby visible companions). Nevertheless, VIRGOHI 21 passes all of the careful tests we have been able to set for it, using the best equipment currently available. Far longer VLA observations might help, but the very low column density and broad velocity width will make VIRGOHI 21 an extremely challenging test for any current interferometer. And if every deep 21 cm detection without an optical counterpart is dismissed out of hand as debris—without considering the timing argument we present in § 3 (which can be used to exclude all previous claims)—one is in effect ruling out, by definition, the detection of any dark galaxy at 21 cm. We cannot of course be certain, but VIRGOHI 21 has turned up in one of the two extremely deep 21 cm surveys where you could most reasonably expect to find a dark galaxy, and it meets all of the criteria we can, in practice, set for such an elusive but potentially vital object today: in particular, such a broad observed velocity width cannot itself be attributed to a tidal interaction if the putative interacting galaxies are well outside the Arecibo beam—as they surely must be here. Future deep H I surveys could reveal a population of such galaxies; with colleagues we are planning such at Arecibo, Jodrell Bank, and Parkes.

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