Many observations indicate that dark matter dominates the extragalactic universe, yet no totally dark structure of galactic proportions has ever been convincingly identified. Previously, we have suggested that VIRGOHI 21, a 21 cm source we found in the Virgo Cluster using Jodrell Bank, was a possible dark galaxy because of its broad line width (~200 km s$^{-1}$) unaccompanied by any visible gravitational source to account for it. We have now imaged VIRGOHI 21 in the neutral hydrogen line and find what could be a dark, edge-on, spinning disk with the mass and diameter of a typical spiral galaxy. Moreover, VIRGOHI 21 has unquestionably been involved in an interaction with NGC 4254, a luminous spiral with an odd one-armed morphology, but lacking the massive interactor normally linked with such a feature. Numerical models of NGC 4254 call for a close interaction ~10$^8$ yr ago with a perturber of ~10$^{11}$ $M_\odot$. This we take as additional evidence for the massive nature of VIRGOHI 21, as there does not appear to be any other viable candidate. We have also used the Hubble Space Telescope to search for stars associated with the H I and find none down to an I-band surface brightness limit of 31.1 ± 0.2 mag arcsec$^{-2}$.

Subject headings: dark matter — galaxies: individual (VIRGOHI 21) — radio lines: galaxies

Online material: color figures, mpeg animation

1. INTRODUCTION

The ability of a galaxy to form stars depends critically on the fraction of its mass that forms the baryonic gas disk and the temperature of this gas. High densities shield the gas from ionizing radiation, allowing it to cool, while higher intensity ionizing radiation keeps the gas hot. Models predict that galaxies can form with gas column densities that prohibit star formation yet provide some self-shielding from the ionizing background (Davies et al. 2006). Such dark galaxies are potentially detectable by blind 21 cm surveys of the sky. The possible existence of dark galaxies has previously been discussed by Jimenez et al. (1997), Hawkins (1997), Verde et al. (2002), and Davies et al. (2006); see also Taylor & Webster (2005) for an alternative view.

Objects detected at 21 cm but with no optical counterparts have been known about for many years; these include high-velocity clouds (Wakker & van Woerden 1997), the Leo Ring (Schneider et al. 1983), and various gas clouds close to bright galaxies (Kilborn et al. 2000; Boyce et al. 2001; Ryder et al. 2001). However, none of these objects have the characteristics of a galaxy, i.e., detectable emission over galaxy-sized spatial scales and a velocity structure consistent with a rotating and gravitationally bound disk. Recently, two candidate dark galaxies have been reported: VIRGOHI 21 (Minchin et al. 2005) and HVC Complex H (Simon et al. 2006). A third possibility is the H I cloud associated with the Local Group galaxy LGS3 (Robishaw et al. 2002).

In this paper we present high-resolution H I observations of VIRGOHI 21, which we believe add further support to our hypothesis that it is a dark galaxy. We also describe Hubble Space Telescope (HST) observations that were specifically designed to search for red giant stars at the distance of the Virgo Cluster and so place very faint limits on the surface density of stars that might be associated with VIRGOHI 21.

2. 21 cm OBSERVATIONS AND ANALYSIS

The new 21 cm data were taken in 2005 March at the Westerbork Synthesis Radio Telescope (WSRT) in two full 12 hr syntheses and reduced using the Miriad package. The data were flagged for shadowing, and on two of the 14 25 m antennas, one polarization was flagged due to problems with the gain. A spectral bandwidth of 10 MHz covered the velocity range 930–3070 km s$^{-1}$. Removal of the noisier end channels left 230 useful channels of width 8.2 km s$^{-1}$ each, giving a velocity resolution of 10 km s$^{-1}$ over the range 980–2890 km s$^{-1}$. Continuum removal was carried out in the UV plane using uv1.in. The standard source 3C147 was used for calibration. Cleaning used a
robust setting of 1, close to normal weighting (Briggs 1995). The cleaned cube was Gaussian-smoothed spatially and Hanning-smoothed in velocity. This was then used as a template for regions where flux was present in the data in order to carry out a deeper cleaning of the dirty image, which gave the final cube used in the analysis. The synthesized beam was $99'' \times 30''$ in size (extended north–south), and the noise was 0.3 mJy beam$^{-1}$ channel$^{-1}$, giving a 5 $\sigma$ column density limit for sources 25 km s$^{-1}$ wide of $2 \times 10^{19} \text{ atoms cm}^{-2}$.

Figure 1a shows a neutral hydrogen (H$\text{i}$) contour map of the field superimposed on a negative optical image. VIRGOHI 21 is the elongated structure in the center (which is at about 2000 km s$^{-1}$). A faint bridge can be seen stretching down to the prominent spiral NGC 4254 (2400 km s$^{-1}$), while the other two sources, NGC 4262 (1350 km s$^{-1}$, upper left) and the faint galaxy C (1750 km s$^{-1}$, immediately to the left of VIRGOHI 21), appear unconnected. Figure 1b shows the velocity-declination projection of the full three-dimensional data cube. Now NGC 4254 is at the bottom right, while VIRGOHI 21 is the angular structure in the center with C to its left. Far more detail can be seen in the animation of the data cube, Figure 2 (available in the electronic edition of the Journal; only the first frame is shown here). The bridge between VIRGOHI 21 and NGC 4254 is clear, as is the lack of any connection between VIRGOHI 21 and either NGC 4262 or galaxy C. The apparent alignment of NGC 4262 with VIRGOHI 21 and NGC 4254 in Figure 1b is merely a consequence of the particular projection shown.

The bridge is $\sim 25''$ long and stretches from 2250 km s$^{-1}$ at $+14^h28^m$ at the low-velocity (western) edge of NGC 4254 to 1900 km s$^{-1}$ at $+14^h41^m$. Here it meets a section of relatively high column density H$\text{i}$ which is flat in velocity until $+14^h46'$, where there is a strong velocity gradient in the opposite direction from that seen in the bridge, rising to 2100 km s$^{-1}$ at $+14^h49'$. Figure 3 is a blown-up image of the source region superimposed on a far deeper CCD optical image. The CCD image was made by combining two B-band images: a 750 s Isaac Newton Telescope (INT) Wide Field Camera (WFC) survey image taken during photometric conditions in 2000 March and our own 600 s image taken with the same instrument during nonphotometric conditions in 2004 May. Both sets of data were reduced using the Wide Field Survey pipeline$^{13}$ which includes debiasing, bad pixel replacement, nonlinearity correction, flat-fielding, and gain correction. The images were combined using the Starlink task MakeMos in the CCDPack package, and photometry was taken from the WFC survey image, which has a photometric accuracy of 0.05 mag. Combined, the two images have a 1 $\sigma$ sky noise of 26.7 mag arcsec$^{-2}$ which has been improved to 27.5 mag arcsec$^{-2}$ by binning into 1'' pixels. This gives a surface brightness detection limit of about 27.5 mag arcsec$^{-2}$ for an object of diameter 10''. We find no optical counterpart down to this surface brightness and size limit.

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$^{13}$ See http://www.ast.cam.ac.uk/~wfcsur/technical/pipeline/.

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There is a small, faint galaxy labeled “A” superposed on the highest $\text{H} \, $contour ($10^{20} \text{ cm}^{-2}$) at declination $+14^\circ 47.4'$. An optical spectrum from the 6.5 m MMT in Arizona shows that it is at a redshift of $z = 0.25$ and is therefore unconnected with VIRGOHI 21 (see Fig. 4). The 17th magnitude galaxy C to the left at $+14^\circ 45'$ is an $\text{H} \, $point source at this resolution. By comparison, VIRGOHI 21 is an extended structure in both dimensions rather than a collection of discrete compact clouds. The velocity-declination plot (Fig. 3b) shows the complex kinematic structure of VIRGOHI 21. The most remarkable feature is the tilted portion between $+14^\circ 46'$ (1900 km s$^{-1}$) and $+14^\circ 49'$ (2100 km s$^{-1}$) which resembles the signature of an edge-on rotating disk (e.g., Kregel et al. 2004). A tentative detection of gas further to the north (in Fig. 3b) could either be part of the interaction or clumps further out in the disk. Note the lack of connection between galaxy C and VIRGOHI 21.

Figures 5 and 6 show the channel maps from the WSRT observations. Figure 5 shows the whole VIRGOHI 21–NGC 4254 system, including the bridge connecting the two which is only a 3 $\sigma$ detection in the individual channels, but taken over all channels, is definitely present (see Fig. 1b and the animation of the data cube, Fig. 2). Figure 6 shows the cube between R.A. $12^h 17^m 46^s$ and $12^h 18^m 03^s$ over the velocity range of VIRGOHI 21. It can be seen that the section identified in Figure 3b as the “Rotating Disk” undergoes a smooth shift northward with increasing velocity, which resembles (taking into account the difference in beam sizes) that observed in edge-on rotating systems (e.g., Uson & Matthews 2003; Rupen 1991). Note that this section of VIRGOHI 21 is unresolved in individual channels, leading to a broadening of the line widths each line of sight to $\sim 100$ km s$^{-1}$ and a lowering of the column density as the $\text{H} \, $is smeared by the beam. The fluxes and masses of all the detected objects and components (taken from the zero-moment map and primary beam corrected) are given in Table 1.

3. HST OBSERVATIONS

To place a better limit on the presence of stars associated with VIRGOHI 21, we have obtained $\text{HST}$ data with a total exposure time of 23,142 s. The Advanced Camera for Surveys (ACS) WFC was used with the $I$-band F814W filter. The pointings were centered on the $\text{H} \, $flux-weighted position of $12^h 17^m 53^s$, $+14^\circ 45'25''$ (J2000.0), with the ACS field of view matching the
Fig. 5.—Channel maps of the VIRGOHI 21–NGC 4254 system. Contours are at −1 mJy (−3 σ), 1 mJy (3 σ), 2 mJy (6 σ), and 3 mJy (9 σ). The beam size is shown by the ellipse in the bottom left, and the velocity of each channel (in km s$^{-1}$) is given in the top left. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 6.—Channel maps of the central region of VIRGOHI 21, with contours as in Fig. 5. The cross indicates the peak of the zeroth-moment map, which is at the center of the rotating component (see Fig. 3). It can clearly be seen that this component (declination range 14°46′ to 14°49′) starts south of this point and moves northward across it with increasing velocity (as might be expected for rotation). [See the electronic edition of the Journal for a color version of this figure.]

| Object | $F_{\text{HI}}$ (Jy km s$^{-1}$) | $M_{\text{HI}}$ ($M_\odot$) |
|--------|-------------------------------|----------------------------|
| NGC 4254 | 91.5 | $5.5 \times 10^9$ |
| NGC 4262 | 7.7 | $4.6 \times 10^8$ |
| Object C | 0.3 | $2 \times 10^7$ |
| Rotating Disk ($14°46′ < \delta < 14°49′$) | 0.6 | $3 \times 10^7$ |
| Low column density bridge ($\delta < 14°41′$) | 1.3 | $8 \times 10^7$ |
| High column density bridge ($14°41′ < \delta < 14°46′$) | 0.8 | $5 \times 10^7$ |
minimum H i size (3.5') very closely. Each orbital exposure was
cr-split in two for cosmic-ray removal and was slightly offset to
permit drizzling.

Preliminary data reduction was done by the Space Telescope
Science Institute with the standard pipeline. The flat-fielded im-
ages have been combined with the IRAF task MultiDrizzle to ob-
tain a distortion-corrected and drizzled final image. The pixel size
in the resulting images is 0.05''.

With this depth and spatial resolution we should be able to re-
solve individual stars in VIRGOHI 21 down to $I \simeq 28$ and thus to
detect the tip of the red giant branch (RGB), which at the distance
of the Virgo Cluster would be close to 27 in $I$. The presence of in-
dividual stars would not conflict with the ground-based INT observ-
ations: the $B$-band surface brightness limit of 27.5 mag would (for
$B - I \simeq 2$) equate to around 0.5 detectable RGB stars arcsec$^{-2}$, or
2500–3000 over the area of VIRGOHI 21.

Stellar photometry was performed with the DAOPHOT pack-
age in IRAF (Stetson 1987). A preliminary selection of stars with a
threshold of 3.5 $\sigma$ was performed with the automatic star-finding
algorithm DAOFIND, and their magnitudes were obtained with the
task phot using an aperture radius of 3 pixels. A spatially
variable model point-spread function (PSF)—with a full width at
half-maximum of 2 pixels—was built with the task psf by selecting
several isolated and bright stars. Finally, allstar was used to fit
the model PSF to the stars in the input list and to produce the final
catalog. The conversion to Johnson $I$ magnitudes and the aperture
correction were done following Sirianni et al. (2005). Artificial
star tests were used to determine the completeness of our selec-
tion; the 50% completeness limit is found to be $I = 27.9$ mag.

We found that the photometry catalog produced with DAOPHOT
allstar (~600 objects) included bad measurements due to mis-
identifications such as parts of bright background galaxies or
unresolved background galaxies whose contribution to the lumin-
osity function is significant at fainter magnitudes (see Durrell
et al. 2002). Given the long exposures required by such observa-
tions we did not ask for additional time to look at another field to
determine the background density of starlike objects; instead, we
have removed objects from our list by individually examining
their radial profiles and rejecting those with a FWHM $\geq 2.5$–
3 pixels, corresponding to the value of the PSF built with the
brightest stars in the field. The final list consists of 281 stars, and
the corresponding luminosity function is shown in Figure 7.

To estimate the contamination due to foreground stars, we
compared the number of detections with a model of the expected
number of Milky Way stars in the position of the Virgo Cluster
(Castellani et al. 2002; Cignoni et al. 2003). This model shows that
the contribution of foreground stars is only significant at brighter
magnitudes ($I \leq 26.5$) where the number of stars detected is small (Fig. 7); at fainter magnitudes, the larger number of detections makes the foreground unimportant.

To search for the tip of the red giant branch (TRGB) we have
applied a Sobel filter to the binned luminosity functions. The lu-
minosity function shows a slope change at $I = 27.2 \pm 0.1$ mag,
which we identify as the possible TRGB. This would place these
stars at a distance of 16.6–18.2 Mpc, which is consistent with
them being in the Virgo Cluster ($d = 16$ Mpc), although the sta-
tistics are poor due to the relatively low number of stars in each
magnitude bin. If we assume this TRGB to be real, despite the
low signal-to-noise ratio (around 2 $\sigma$ on the Sobel filter output),
we can set the most stringent limit on the surface brightness of
VIRGOHI 21.

Assuming (very generously) that all of the fainter stars are
also at the distance of the cluster (119 with $I = 27.2$–27.9), they
have a combined magnitude of $I = 22.3$, giving a surface bright-
ness of 33.8 $I$ mag arcsec$^{-2}$. Using the formula of Durrell et al.
(2002) gives a correction for only having the top 0.7 mag of the
RGB of 1.5 $\pm 0.1$ mag arcsec$^{-2}$. We do not detect any asym-
totic giant branch stars; based on the work of Durrell et al., these
could contribute another 0.2 $\pm 0.1$ mag arcsec$^{-2}$. Overall, this
gives an upper limit for the total $I$-band surface brightness of
31.1 $\pm 0.2$ mag arcsec$^{-2}$. For normal galaxy colors of $B - I = 1.5$–2,
this equates to an extremely faint $B$-band surface bright-
ness of 32.4–33.3 mag arcsec$^{-2}$.

These results can be compared with studies of Virgo Cluster
intergalactic stars (Durrell et al. 2002) and those used to deter-
mine the color-magnitude diagrams of dwarf galaxies belonging
to the cluster (Caldwell 2006). Durrell et al. imaged a field at
about 40' northwest of M87 ($\approx 190$ kpc), while the two fields
observed by Caldwell were also relatively close to the center of
Virgo, one at 1.4' north ($\approx 400$ kpc) and the other at 1.1' west
($\approx 315$ kpc). These fields are much closer to M87 at the center of
the cluster than VIRGOHI 21, and the number density of stars
found is also much higher; however, there is an apparent de-
crease in the number of stars as one moves away from the cluster
center (see Fig. 9 in Caldwell [2006] and Fig. 6 in Durrell et al.
[2002]). A comparison between the estimated surface brightnesses
of the three fields shows that $\mu_I$ ranges from 27.7 $I$ mag arcsec$^{-2}$
(Durrell et al. 2002) for the fields closer to the cluster center to 27.9
and 29.9 $I$ mag arcsec$^{-2}$ (Caldwell 2006) for the more distant ones.
Our $I$-band surface brightness of 31.3, at a projected distance of
1.1 Mpc from the cluster center (M87), is thus consistent with
the known population intracluster stars in Virgo, and so there is
no evidence to suggest that our detections are associated with
VIRGOHI 21 in any way.

4. DISCUSSION

In the previous sections we have described our new observa-
tions of VIRGOHI 21. In this section we try and put them in
context, and we particularly want to assess the evidence for
against the dark galaxy hypothesis.

1. If attributed to gravitation, changes in velocity of galactic
size over galactic scales, as seen here, require masses of galactic
proportions. On dimensional grounds the abrupt change in ve-
cocity $\Delta V$ ($\approx 200$ km s$^{-1}$) seen in VIRGOHI 21 over a conser-
vative length scale $\Delta x$ ($\approx 14$ kpc $\approx 5 \times 10^{22}$ cm $\approx 3'$ at the Virgo

Fig. 7.—Luminosity function of the final list of stars. The dotted line shows
the output of the edge detection filter used to detect the tip of the RGB. The
maximum of the function indicates the position of the tip. The vertical line at
$I = 27.9$ mag indicates the 50% completeness limit.
Cluster distance of 16 Mpc) implies a mass $M \geq (\Delta V)^2 \Delta v / G \simeq 10^{10} - 10^{11} M_\odot$, if this is due to an object rotating in dynamical equilibrium. If the velocities are not due to rotation, then changes in velocity like this can be observed if, for example, we are observing an arc of gas and our view is almost edge-on. These geometrical effects can lead to large velocity widths that may resemble rotation (e.g., Bournaud et al. 2004). The problem with this latter scenario (as also pointed out by Vollmer et al. [2005]) is that the perturbing galaxy should be moving in the plane of the arc and so should be projected on the sky very close to it. We can simply quantify what we mean by this. Imagine two galaxies with radial velocities $V_1$ and $V_2$ at either end of an approximately linear tidal bridge of physical length $d$ pitched at an angle $\theta$ to the line of sight. A telescope pointed toward it has a transverse beam diameter of $b$ at the bridge. The only significant gas motions within the bridge will be streaming velocities along its length. From end to end of the bridge, the radial velocity difference is $|V_2 - V_1|$, while within the telescope beam, the measured velocity width $\Delta V$ will be $(b/d \sin \theta)(|V_2 - V_1|)$. But, bridges of any appreciable size arise only when the total velocity difference between the interacting galaxies, i.e., $|V_2 - V_1|/\cos \theta$, is of order the circular velocity $V_c$ in the galaxies involved (Toomre & Toomre 1972). It follows that $\Delta V/|V_2 - V_1| \approx (b/d) \cos \theta$. Thus, broad line widths $\Delta V \approx V_c$, as here, can only be seen within a beam if both interactors appear to lie within or very close to the beam, i.e., $d \sin \theta < b \cos \theta < b$. We can find no potential perturber within the Arecibo beam ($b \approx 3.6\arcmin$) or close to it. Thus, we do not believe VIRGOHI 21 can be tidal debris from an interaction of this nature.

2. The existence of the H1 bridge indicates that NGC 4254 has undergone some kind of interaction. NGC 4254 is a luminous one-armed spiral galaxy sufficiently peculiar to have attracted several studies (Iye et al. 1982; Phookun et al. 1993; Vollmer et al. 2005). According to Vollmer et al. (2005), the morphological peculiarities of NGC 4254 can be explained by an interaction with a perturbing mass of $\sim 10^{11} M_\odot$. As it is now clear that VIRGOHI 21 is involved in this interaction, it should be considered a candidate for the perturber, particularly as no other candidate can be easily identified. The Vollmer et al. simulation implies an interaction $3 \times 10^9$ yr ago. As the projected length of the bridge is 120 kpc, this would imply it has been drawn out at a projected speed of 390 km s$^{-1}$, which is comparable to the radial velocity difference between NGC 4254 and VIRGOHI 21 of 400 km s$^{-1}$. Thus, if VIRGOHI 21 were massive enough ($\sim 10^{11} M_\odot$), it could be the cause of the tidal bridge.

3. If object C, the H1 galaxy just to the east (left) of VIRGOHI 21 (Fig. 3) were involved, its mass (see item 1 above) should be $\sim 10^{11} M_\odot$. However, its measured H1 velocity distribution and size suggest a probable mass $\leq 10^9 M_\odot$, while it has a luminosity of only $10^8 L_\odot$, and a $M_{HI}$ of $2 \times 10^7 M_\odot$. Galaxy C appears to be 2 orders of magnitude too underluminous and underluminous to explain the one-armed spiral structure of NGC 4254 and the H1 bridge connecting to it. So, it seems very unlikely that C has sufficient mass to cause a perturbation of over 200 km s$^{-1}$ to the tidal stream, and VIRGOHI 21 passes to its west, not between it and NGC 4262 as might be expected if it had pulled the stream westward. The radial velocity of C means that it must be moving past the stream at a velocity (relative to the putative undisturbed velocity of the stream) of at least 350 km s$^{-1}$. At this speed, it would not have stayed close to the stream long enough to have severely disturbed it. It would also be expected that if C were involved in the interaction, then there would be gas falling onto it, but this does not appear to be the case as there is no gas seen between VIRGOHI 21 and C. The H1 in C is unresolved, implying that it is confined to the area of the optical galaxy; it shows no signs of infalling gas streams or any other disturbance. Galaxy C is in our a minds a possible, but highly unlikely participant in this interaction.

4. Recently, Bekki et al. (2005) have published numerical simulations on the basis of which they argue that “VIRGOHI 21... is likely to be tidal debris rather than a dark galaxy.” They model high-speed, hyperbolic interactions within cluster potentials (at 350 and 700 kpc from the cluster center) over 2 Gyr in order to draw out very long tidal tails where the H1 and stars have become separated so that the average surface brightness within a 100 kpc$^2$ box is $\geq 30$ mag arcsec$^{-2}$, assuming $M_*/L_\odot = 4$. The Bekki et al. stellar density can be converted to $I$-band if we assume a value for $M_*/L_I$. Estimates of this vary (e.g., Portinari et al. 2004; Vallejo et al. 2002; McGaugh & de Blok 1997), but are generally close to 1 and always less than 2. We therefore adopt a very conservative (in the sense of producing the lowest $I$-band surface brightness) value of $M_*/L_I = 2$. This gives a value of $B - I$ for the surface brightness estimates given in Bekki et al. of 0.75. For the two double-tailed models presented (M1 and M2), this gives average $I$-band surface brightnesses of 32.7 and 33.0 mag arcsec$^{-2}$, respectively, while for the two single-tailed models presented (M3 and M4), this gives average $I$-band surface brightnesses of 29.5 and 29.9 mag arcsec$^{-2}$, respectively. The two-tailed models are inconsistent with our H1 data and the H1 data of Phookun et al., which clearly show a single tail from NGC 4254, while the single-tailed models give considerably higher surface brightnesses (1.2–1.6 mag, or 6–8 $\sigma$) than the upper limit from our HST observations. In addition to this, Bekki et al. find that the velocity fields produced in the dark clouds by their models do not resemble rotation, concluding that “velocity fields are the key observational tools to help us determine whether gas clouds are (unbound) tidal debris or are self-gravitating systems embedded within a massive dark matter halo.” From both the surface density of stars expected in a single-tail interaction and from the rotation curve, it appears that high-speed, hyperbolic interactions within a cluster potential like those proposed by Bekki et al. are unable to reproduce our new observations of VIRGOHI 21.

5. NGC 4262, the spiral to the northeast, does not appear to be involved. This is not surprising because it is in totally the wrong place to give rise to a tidal feature like that observed (NGC 4262, NGC 4254, and VIRGOHI 21 form a well-separated triangle on the sky; see also Vollmer et al. 2005). In addition, the radial velocity between NGC 4254 and NGC 4262 is far too large (900 km s$^{-1}$) to generate tidal features such as bridges and tails. Furthermore, with such a large radial velocity difference between NGC 4254 and NGC 4262, any interaction must be at high speed and, as seen above from the simulations of Bekki et al., such interactions are not capable of reproducing our observations, as even the most isolated gas clouds formed in single-tail systems have surface brightnesses 1.5–2 mag brighter than the limit set by our HST observations. NGC 4262 is a S0 galaxy with an H1 ring that is inclined with respect to the optical disk (Krumm et al. 1985). Krumm et al. present higher resolution H1 observations than our data, and they say that if the H1 has come from an interaction, “the narrowness of the ring and the undisturbed appearance of the optical disk suggest that the donor was a gas-rich dwarf galaxy or intergalactic H1 cloud, rather than a massive spiral.” Thus, we find it very difficult to see how NGC 4262 could have given rise to the features we have now observed.

6. The components of VIRGOHI 21 are connected both spatially and in velocity, making it exceedingly improbable that they could be chance superpositions of smaller hydrogen clouds, while the bridge to NGC 4254 is not explained by this hypothesis.
The lack of any visible companion to NGC 4254 has thus
particularly so, given the lack of any other candidate. Near a strong concentration of H\textsc{i} around 60 kpc from the center of the system (for a distance of 13.8 Mpc; Saviane et al. 2004). However, the major problem with this hypothesis is that NGC 4254 apparently shows no sign of having undergone a recent merger. It would be expected that a merger violent enough to have thrown out an arm over 100 kpc in length would leave some imprint on the optical disk, but this is not the case here. Phookun et al. found that “the galaxy is undergoing an interaction that is not so strong or violent as to disrupt the disk.” While this fits with the hypothesis of VIRGOHI 21 as a dark galaxy, playing a role similar to that of the companions of NGC 4027 or NGC 4654 in exciting the n = 1 mode, it does not fit the merger scenario.

8. Oosterloo & van Gorkom (2005) argue that another H\textsc{i} cloud in the Virgo Cluster, VIRGOHI 4 (Davies et al. 2004), is caused by ram pressure stripping from NGC 4388 due to an interaction with the hot gas halo of the M86 subgroup and suggest a similar origin could be possible for VIRGOHI 21. This would explain the bridge without the need to invoke a second galaxy, either interacting or merging. However, we cannot see how this can give the steep, reversed velocity gradient seen in VIRGOHI 21, nor does it explain the distortion to the optical disk of NGC 4254.

9. Single-armed spirals are normally the result of interactions with close-by massive companions (Iye et al. 1982; Phookun et al. 1993); the lack of any visible companion to NGC 4254 has thus led to a number of observations and dynamical models. As mentioned above, recent numerical models by Vollmer et al. (2005) suggest that NGC 4254 “had a close and rapid encounter with a 10^{11} M_{\odot} galaxy, velocity gradient as the NGC 4254 end of the ‘bridge’ between the two objects. This supports our inference that VIRGOHI 21 is the aforesaid 10^{11} M_{\odot} mass which caused the peculiarities in NGC 4254—particularly so, given the lack of any other candidate.

If our hypothesis is correct that this is a dark, gravitationally bound, edge-on rotating disk, then its properties are as presented in Table 2. Judging from visible disk galaxies, whose masses continue to rise beyond their H\textsc{i} edges (e.g., Salucci & Persic 1997), the full size and mass of such a disk could easily reach the ~10^{11} M_{\odot} required by the Vollmer et al. (2005) simulations. The very low surface brightness limits give an upper limit to the luminosity of the disk of 1.9 \times 10^{9} L_{\odot}, giving a lower limit for M_{Bol}/L_{B} of at least 10^{6} M_{\odot}/(1 L_{\odot}), whereas normal galaxies have values <50.

It is clear from our new observations that VIRGOHI 21 is intimately linked to NGC 4254. The important question is whether it is the cause of the H\textsc{i} bridge or the effect of some previous encounter. We believe the weight of the evidence presented above lies on the side of a dark galaxy. Dark halos have, after all, been predicted by galaxy evolution simulations such as Jimenez et al. (1997), Verde et al. (2002), and Davies et al. (2006). That none have been confirmed so far is most probably due to instrumental limitations. VIRGOHI 21 itself was missed in the normal HIPASS-sensitivity observations of this area, and only picked up with 10 times longer integrations in the VIRGOHI survey. In any case, single-dish angular resolution makes it all too easy to confuse a dark cloud with a bright object clustered with it (Davies et al. 2006). The recent optical identification program for HIPASS sources (Doyle et al. 2005) can rule out only “isolated,” i.e., unclustered, dark galaxies.

5. SUMMARY

In this paper we have presented new Westerbork high-resolution 21 cm observations of a H\textsc{i} source (VIRGOHI 21) that we have previously observed at Jodrell Bank and Arecibo. These observations clearly show that VIRGOHI 21 has played a part in some form of interaction with the bright spiral galaxy NGC 4254. Whether VIRGOHI 21 is the result of some previous interaction with a third object or it is the interacting object itself is still open to conjecture. We have argued in this paper that the weight of evidence now resides on the side of the latter rather than the former conjecture. This is primarily because the new observations show a long drawn-out tidal feature which has an abrupt velocity change and we cannot find a candidate galaxy to have caused it. Tidal interactions between optically bright galaxies often draw out stars as well as gas. We have also used HST to search for stars associated with VIRGOHI 21 and find none down to very faint surface brightness levels. We look forward to new observations and numerical models that will add further weight to either side of this debate.

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