A Dark Galaxy in the Virgo Cluster Imaged at 21-cm.

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ABSTRACT

Dark Matter supposedly dominates the extragalactic, yet no totally dark structure of galactic proportions has ever been convincingly identified. Earlier (Minchin et al. 2005) we suggested that VIRGOHI 21, a 21-cm source we found in the Virgo Cluster at Jodrell Bank using single-dish observations (Davies et al. 2004), was probably such a dark galaxy because of its broad line-width (∼ 200 km s⁻¹) unaccompanied by any visible gravitational source to account for it. Now we have managed to image VIRGOHI 21 in the neutral-hydrogen line, and indeed we find what appears to be a dark, edge-on, spinning disc with the mass and diameter of a typical spiral galaxy. Moreover the disc has unquestionably interacted with NGC 4254, a luminous spiral with an odd one-armed morphology, but lacking the massive interactor invariably responsible for such a feature. Published numerical models (Vollmer, Huchtmeier & van Driel 2005) of NGC 4254 call for a close interaction ∼ 10⁸ years ago with a perturber of ∼ 10¹¹ solar masses. This we take as completely independent evidence for the massive nature of VIRGOHI 21.

Key words: dark matter – galaxies: individual (VIRGOHI 21) – radio lines: galaxies

1 INTRODUCTION

Cold Dark Matter (CDM) models of galaxy formation predict many more dark matter halos than are observed as galaxies (Kauffmann, White & Guiderdoni 1993; Moore et al. 1999; D'Onghia & Lake 2004). Whether stars can form in dark matter halos depends critically on the fraction of baryons (m_d) that can be trapped and retained by each halo (for previous discussions about the existence and formation of dark galaxies see Jimenez et al. 1997; Hawkins 1997; Verde et al. 2003). Some of those that retain a small fraction of their original baryons (m_d < 0.05) are able to form stable gaseous disks, but because of the low gas densities they are not able to form stars. The physical state of the gas in the disc is very dependent on its density and temperature with the latter influenced by the intensity of any ionising background. 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. in prep.). Such dark galaxies are potentially detectable by blind 21cm surveys of the sky.

Objects detected at 21cm 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. 2001; Boyce et al. 2001a; 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 disc.

In a previous paper (Minchin et al. 2005) we described Jodrell Bank and Arecibo observations of VIRGOHI 21 an HI source discovered during a survey of the Virgo cluster (Davies et al. 2004). VIRGOHI 21 has all of the HI characteristics of a typical rotating disc galaxy, but no detectable optical emission. Our conclusion was that VIRGOHI 21 was an extremely promising candidate for the first dark galaxy. In this paper, we present high resolution HI observations of this source, which add to the conclusions drawn in the earlier paper that this is, indeed, a massive dark galaxy.
2 OBSERVATIONS AND ANALYSIS

The new data were taken in March 2005 at the Westerbork Synthesis Radio Telescope (WSRT) in two full 12-hour syntheses and reduced using the MIRIAD package. The data were flagged for shadowing and on two of the fourteen 25-metre antennae one polarisation 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 to 2890 km s\(^{-1}\). Continuum removal was carried out in the UV plane using Uvlin. The standard source 3C147 was used for calibration. Cleaning used a robust setting of 1, close to normal weighting \(^{(\text{Briggs} 1995\text{)}}\). The cleaned cube was gaussian smoothed spatially and Hanning smoothed in velocity, and then used for a second-pass deeper cleaning which gave the final cube used in the analysis. The synthesised beam was 99' \times 30'\,\textprime\, in size (extended North-South) and the noise was 0.3 mJy beam\(^{-1}\) channel\(^{-1}\), giving a 5\,\sigma\, column-density to sources 25 km s\(^{-1}\) wide of 2 \times 10\(^{19}\) Hydrogen atoms cm\(^{-2}\).

Fig. 1a shows a neutral Hydrogen (H\,i) contour map of the field superimposed on a negative optical image. VIRGOHI 21 is the elongated structure in the centre (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 (1500 km s\(^{-1}\), upper left) and the faint galaxy 'C' (1750 km s\(^{-1}\), immediately to the left of VIRGOHI 21) appear unconnected. Fig. 1b shows the velocity-declination projection of the full 3 dimensional data cube. Now NGC 4254 is at the bottom right while VIRGOHI 21 is the angular structure in the centre. C is to its left. Far more detail can be seen on an animation which is available at [http://www.astro.cf.ac.uk/groups/galaxies](http://www.astro.cf.ac.uk/groups/galaxies) for instance the bridge is clear and obvious, as is the lack of any connection between VIRGOHI 21 and either NGC 4262 or C. The apparent alignment of NGC 4262 with VIRGOHI 21 and NGC 4254 in Fig. 1b is a consequence of the particular projection shown.

The \(\sim 25\) arcmin filamentary bridge stretches from the low-velocity (western) edge of NGC 4254, falling gently in radial velocity from 2250 km s\(^{-1}\) at declination +14\,\textdegree\,20' to 1900 km s\(^{-1}\) at +14\,\textdegree\,41' where it is suddenly arrested. Then at +14\,\textdegree\,46' it is abruptly wrenched upwards again towards 2100 km s\(^{-1}\) at 14\,\textdegree\,49'.

Fig. 2 is a blow-up of the source region superimposed on a far deeper CCD optical image, illustrating that there is no optical counterpart \(^{(\text{Minchin et al.} 2005\text{)}}\). An optical spectrum from the 6.5-m MMT in Arizona of the small, faint galaxy 'A', which is superposed on the highest H\,i contour (1 \times 10\(^{20}\) cm\(^{-2}\)) at declination +14\,\textdegree\,47\,\textprime\,4, shows that it is at a redshift of \(z = 0.25\) and is therefore unconnected with VIRGOHI 21. The 17th magnitude galaxy 'C' to the left at +14\,\textdegree\,45' is an H\,i 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 (right) shows the complex kinematic structure of VIRGOHI 21. The most remarkable feature is the tilted portion between +14\,\textdegree\,46' (1900 km s\(^{-1}\)) and +14\,\textdegree\,49' (2100 km s\(^{-1}\)) which resembles the signature of an edge-on rotating disc \(^{(\text{Kregel, van der Kruit & de Blok} 2004\text{)}}\), which is what we take it to be. Gas further to the North and in particular to the South could either be part of the interaction or be clumps further out in the disc. Note the lack of connection between galaxy 'C' and VIRGOHI 21.

3 DISCUSSION

Combining the new data with the old, we argue:

(a) 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 velocity wrench \(\Delta V (\sim 200\) km s\(^{-1}\)) seen at VIRGOHI 21 over a conservative length-scale \(\Delta x (\sim 14\) kpc \(\approx 5 \times 10^{22}\) cm \(\approx 3\) arcmin) at the Virgo Cluster distance of 16 Mpc \(^{(\text{Minchin et al.} 2005\text{)}}\) implies a mass \(M \geq (\Delta V)^2 \Delta x / G \approx 10^{10-11}\) solar masses. More specifically the gravitational (free-fall) timescale \((\Delta x)^{3/2} / (GM)^{1/2}\) needs to be \(\leq \Delta x / V\), the time it takes for gas travelling at \(V\) (relative to \(M\)) to change velocity by \(\Delta V\). And where \(\Delta V \sim V\), as it appears to be here (see Fig. 2b), \(M \geq (\Delta V)^2 \Delta x / G\) again. For non-gravitational alternatives see below.

(b) The bridge between NGC 4254 and VIRGOHI 21 reveals that they have interacted. According to published numerical simulations \(^{(\text{Vollmer et al.} 2003\text{)}}\) (below) the morphological peculiarities of NGC 4254 require a perturbing mass of \(\sim 10^{11}\) M\(_{\odot}\) – providing independent evidence that VIRGOHI 21 weighs \(\approx 10^{11}\) M\(_{\odot}\). The simulation implies an interaction \(3 \times 10^8\) years ago. As the projected length of the bridge is \(120\) kpc this would imply it has been drawn out at a projected speed of \(300\) km s\(^{-1}\), which is comparable to the radial velocity difference between NGC 4254 and VIRGOHI 21 of \(400\) km s\(^{-1}\).

(c) NGC 4262, the spiral to the North-East, is not involved. There is no bridge to it (see animation) and the radial velocity difference between NGC 4254 and NGC 4262 is too large (\(900\) km s\(^{-1}\)) to generate one.

(d) If object C, the H\,i galaxy just to the east (left) of VIRGOHI 21 (Fig. 2) were involved its mass, by (a), must be \(\sim 10^{11}\) M\(_{\odot}\). However its measured H\,i velocity distribution and size suggest a probable mass \(\lesssim 10^8\) M\(_{\odot}\), while it has a luminosity of only \(10^8\) L\(_{\odot}\). It is two orders of magnitude too undermassive and underluminous to explain the dynamics of VIRGOHI 21, while there is no sign of its interacting.

(e) The structure of VIRGOHI 21 (Fig. 2a) is centred at R.A. \(12^h 17^m 52^s\) and elongated in the North-South plane between +14\,\textdegree\,41' and +14\,\textdegree\,49'. Its remarkable velocity change (from 1900 to 2100 km s\(^{-1}\)) is, however, confined to the tilted structure (Fig. 2b) between +14\,\textdegree\,46' and +14\,\textdegree\,49', which closely resembles the characteristic shape of an edge-on disc \(^{(\text{Kregel et al.} 2004)}\). If indeed what we are witnessing here is a dark, gravitationally bound, edge-on rotating disc then its properties are as presented in Table 1 with a minimum mass of \(2 \times 10^{10}\) M\(_{\odot}\). Judging from visible disc galaxies, whose masses continue to rise beyond their H\,i edges \(^{(\text{Salucci} 1997)}\), the full size and mass of such a disc could easily reach \(\sim 10^{12}\) M\(_{\odot}\). The very low surface-brightness limits (dimmer than 27.5 B mag arcsec\(^{-2}\) \(^{(\text{Minchin et al.} 2005\text{)}}\)) imply that the disc has a \(M_{dyn}/L_B\) ratio of at least 750 M\(_{\odot}\)/L\(_{\odot}\) where normal galaxies have \(< 50\). Deep HST observations, capable of reaching individual Red Giant stars in VIRGOHI 21, are in hand.
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Figure 1. (a) H\textsc{i} contour map of the 21-cm observations, superimposed on a 1 square degree negative Digitized Sky Survey image. Contours are from $2.5 \times 10^{19}$ to $2 \times 10^{20}$ cm$^{-2}$ at intervals of $2.5 \times 10^{19}$ cm$^{-2}$.(b) Shows the declination-velocity projection of the data cube. More detail can be seen in the on-line animation of the cube.

Figure 2. As Fig. 1, but expanded and superimposed on a negative of our deep CCD B-band image (Minchin et al. 2005) with a surface-brightness limit of 27.5 B mag. arcsec$^{-2}$.

Table 1. PROPERTIES OF THE DARK DISC

| Property                  | Value                      |
|---------------------------|----------------------------|
| Diameter $2R$, [from $+14^\circ46'$ to $49'$] | 14 kpc                     |
| Circular Velocity $V_c$, [(2100 – 1900)/2] | 100 km s$^{-1}$            |
| Spin Period $P$, [2$\pi R/V_c$]              | $4 \times 10^8$ years      |
| Total Mass $M_T$, [$RV_c^2/G$]                | $2 \times 10^{10}M_\odot$ |
| Face-on Mass-density [$M_T/\pi R^2$]          | $2 \times 10^{-2}$ g cm$^{-2}$ |
| Hydrogen Mass $M_{HI}$, [$F_{HI} = 0.7$ Jy km s$^{-1}$] | $4 \times 10^7 M_\odot$ |
| Face-on gas density $N_{HI}$, [$M_{HI}/\pi m_H R^2$] | $3 \times 10^{19}$ cm$^{-2}$ |
| Total Mass to Blue Light Ratio $M_{HI}/L_B$    | $> 750 M_\odot/L_\odot$    |

The integrated spectrum, minus the bridge, is consistent with earlier single-dish observations, implying that the interferometer misses little H\textsc{i}. The surprising ease with which it has been mapped is due to two pieces of luck: it is edge on, thus increasing the apparent surface density, and most of its gas is spread over fairly low velocity widths within each synthesised beam.

The incontrovertible evidence (see animation) of an interaction with NGC 4254 provides independent support for the massive nature of VIRGOHI 21. NGC 4254 is a luminous one-armed spiral galaxy sufficiently peculiar to have attracted several studies (Iye, Okamura & Watanabe 1982; Phookun, Vogel & Mundy 1993; Vollmer et al. 2005). Single-armed spirals are invariably the result of interactions with close-by massive companions (Iye et al. 1982). The lack of any visible companion thus triggered observations and dynamical models. Recent numerical models by Vollmer et al. (2005) indicate that NGC 4254 “had a close and rapid encounter with a $10^{11} M_\odot$ galaxy $\sim 250$ Myr ago. The tidal interaction caused the spiral structure...”. Phookun et al. (1993), in a VLA study of the galaxy, find a trail of gas leading away from it (their Figure 5) in both the right direction and with exactly the right velocity-gradient required to intersect VIRGOHI 21. Thus the case for VIRGOHI 21 being the aforesaid $\sim 10^{11} M_\odot$ mass which caused the peculiarities in NGC 4254 seems strong. A detailed simulation which includes our new data could remove any doubt.

Models for VIRGOHI 21 now have a number of crucial observations to explain: the broad velocity-width in a galactic volume (implying large mass); its elongated geometry; its steep velocity profile; the bridge to NGC 4254, and to no
other galaxy; the damage to NGC 4254 (large mass); and the lack of light. Given the above observations we now discuss a number of hypotheses as to the origin of VIRGOHI 21 and its associated H\textsc{i}.

(a) We are detecting tidal debris left by the past interaction of NGC 4254 and another galaxy.

This is rather easy to dismiss here where the lines are so broad, and there are no such interactors visible in the immediate vicinity. 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 plane of the sky. A telescope pointed towards 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 \( (b/d \sin \theta) \times |V_2 - V_1| \). But, as is well known, bridges of any size arise only when the total velocity difference between the interacting galaxies \( - |V_2 - V_1|/\cos \theta \) here – of is the same order as the circular velocity \( V_c \) in the donor (Toomre & Toomre 1972). It follows immediately that \( \Delta V/V_c \simeq (b/d) \tan \theta \). Thus broad line widths \( \Delta V \simeq V_c \), as here, can only be seen within a beam if both interactors appear to lie within, or very close to the beam \( (d \cos \theta < b) \). There are no such putative interactors even within the Arecibo beam \( (b \simeq 3.6') \) close to it, otherwise we would see them in Fig. 2a. VIRGOHI 21 cannot be such tidal debris. And one cannot escape this conclusion by presupposing a very ancient interaction almost along the line-of-sight \( (\theta \sim 90^\circ) \) – if so, where is the culprit? Bekki, Koribalski & Kilborn (2005b) have carried out numerical simulations to model interactions that might lead to tidal features detectable at 21 cm. They have proposed an interaction with NGC 4254 as the likely cause of VIRGOHI 21. Their Model 1, which does create a cloud of the right velocity width – because of its projection along the line of sight, fails to show the perturbing galaxy, and in any case would never have been claimed as a plausible dark-galaxy candidate by us because it would fail the stringent ‘timing-argument’ explained in our previous paper (Minchin et al. 2002). Additionally, the sense of their velocity field relative to the donor, NGC 4254, is opposite to the sense actually observed. Their favoured Model 4, which does indeed recreate the disturbance of NGC 4254, has a velocity width of 20, not 200, km s\(^{-1}\)! In fact, their simulations demonstrate just how hard it is to explain VIRGOHI 21 as tidal debris.

Other hypotheses have also been put forward, and should be examined to see if they can explain our observations:

(b) Two superposed H\textsc{i} Clouds.

The components of VIRGOHI 21 are connected both spatially and in velocity, making it exceedingly improbable that they could be chance superpositions of clouds, while the bridge to NGC 4254 is not explained by this hypothesis.

(c) A tidal tail from a galaxy merging with NGC 4254.

Phookun et al. (1993) suggested that the distortion of NGC 4254 could be due to infalling gas-clouds. Could VIRGOHI 21 be a tail, similar to those seen in UGC 10214 (Briggs et al. 2001) or NGC 4038/9 (Gordon, Koribalski & Jones 2001)? In NGC 4038/9, in particular, there is what appears to be a tidal dwarf near a strong concentration of H\textsc{i} at the end of the southern tail, around 60 kpc from the centre of the system (for a distance of 13.8 Mpc; Saviane, Hibbard & Rich 2004).

Although this hypothesis can, at first sight, explain the WSRT observations, with the bridge as an H\textsc{i} tail and VIRGOHI 21 as a tidal dwarf forming in a concentration at the tip, it is clear on more detailed examination that this cannot be the case. The velocity field in VIRGOHI 21 changes direction in a way not seen in examples of tidal dwarfs, and to a much greater extent – the tidal dwarf in the NGC 4038/9 system, for instance, has a gradient in the same sense as the gas in the tail nearby, whilst VIRGOHI 21’s gradient is in the opposite direction and has twice the velocity width. Even more troubling for this hypothesis, NGC 4254 does not show signs of having recently merged with another \( L^* \) sized galaxy – and yet it would have had to do so to have thrown out a tidal tail twice as long as that from the violently interacting NGC 4038/9 system.

(d) A high column-density part of a giant H\textsc{i} ring.

Bekki et al. (2005b) propose that some H\textsc{i} clouds without optical counterparts could be the high-density regions of H\textsc{i} rings. In their scenario, objects such as the Leo Ring (Schneider et al. 1983) are formed by the tidal stripping of low surface-brightness galaxies with extended gas disks. As the column-density varies around the ring, it is possible that only part of it will be detectable – possibly at a large distance from the original galaxy from which the gas has been stripped. This would then be identified as an intergalactic H\textsc{i} cloud.

While this hypothesis might have explained the single-dish observations, it is hard to make the WSRT data fit. The ring should be orbiting around a large centre of mass to the east of VIRGOHI 21 and at a higher velocity, which cannot be identified. Also, if the bridge is part of the ring, then it is unconnected with the perturbation of NGC 4254 – which is both very unlikely and leaves the single-arm mode of that galaxy unexplained.

(e) A three-body interaction.

It might be that a third mass, possibly object C, has interfered with the interaction between NGC 4254 and another body (possibly NGC 4262, as proposed by Vollmer et al. 2004, as there are no other obvious candidates). However, 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 at that point of 2100 km s\(^{-1}\) – the velocity of the high-velocity end of VIRGOHI 21) 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. Nor does C show any signs of being disturbed itself; its H\textsc{i} is unresolved, implying that it is confined to the area of the optical galaxy, and its optical image similarly shows no sign of any perturbation.

(f) Ram pressure stripping.
Oosterloo & van Gorkom (2005) argue that another H\textsubscript{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 sub-group 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, this cannot give the steep, reversed velocity gradient seen in VIRGOHI 21, nor does it explain the distortion to the optical disk of NGC 4254. Ram pressure stripping does not, therefore, appear to work as an explanation of this system.

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**4 CONCLUSIONS**

Models for VIRGOHI 21 now have a number of crucial observations to explain: the broad velocity-width in a galactic volume (implying large mass); its elongated geometry; its steep velocity profiles; the bridge to NGC 4254, and to no other galaxy; the damage to NGC 4254 (large mass); and the lack of light. Of other models that have been suggested, or that we have been able to devise, neither tidal debris, nor Ram Pressure Stripping nor a Group gravitational field, nor long-range interactions deliberately aimed at simulating this object can explain the abrupt changes of velocity.

The new observations make it even harder to escape the inference that VIRGOHI 21 contains a massive dark disc.