SWIFT XRT OBSERVATIONS OF THE POSSIBLE DARK GALAXY VIRGOHI 21

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Abstract

Swift XRT observations of the H i line source VIRGOHI 21 were performed on 2008 April 22 and 26 for a total exposure time of 9.2 ks. This is the first pointed X-ray observation of VIRGOHI 21, a putative dark galaxy in the Virgo Cluster, and no photons were detected from this source. The nondetection of extended X-ray emission within the angular extent of the H i source corresponds to a 99% confidence upper limit of 2.1 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1} in the 0.3–2.0 keV band. The equivalent upper limit to the amount of diffuse hot gas associated with VIRGOHI 21 is in the range 4 \times 10^{-2}–2 \times 10^8 M_\odot, for a hot gas temperature between 0.1 and 1 keV. The nondetection also corresponds to a 99% confidence upper limit on the flux from a pointlike source of 8 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} in the 0.3–2.0 keV band. We discuss the constraints on the nature of VIRGOHI 21 imposed by these observations and the theoretical implications of these results.

Subject headings: dark matter — galaxies: individual (VIRGOHI 21) — X-rays: galaxies

1. INTRODUCTION

H i surveys of the Virgo Cluster (Davies et al. 2004, 2006; Minchin et al. 2005, 2007; Haynes et al. 2007) have revealed a remarkable H i cloud, VIRGOHI 21, with apparent evidence of rotation yet unaccompanied by any optical emission. The H i mass (M_i \sim 3 \times 10^7 M_\odot), inferred circular velocity (V \sim 100 \text{ km s}^{-1}), and physical size (R \sim 8 \text{ kpc}) are all typical of luminous galaxies of dynamical masses 10^{10}–10^{11} M_\odot, yet deep optical follow-up observations provide an upper limit of only 31.1 \text{ M}_\odot \text{ arcsec}^{-2}, corresponding to a stellar content of 2 \times 10^8 L_\odot (Minchin et al. 2007). Thus, VIRGOHI 21 is currently considered the prototypical dark-matter-dominated galaxy with a rotating gaseous disk but devoid of stars.

If VIRGOHI 21 is a massive dark galaxy, then it has important implications for the theory of structure formation. The highly successful cosmological hierarchical clustering model originated by White & Rees (1978) is based on the idea of accretion and merging of cold dark matter (CDM) from small sizes (\sim 10^5 M_\odot) up to the large galaxy clusters observed at the present epoch. The CDM model predicts a large number of \sim 10^5 M_\odot dark matter (DM) halos should remain unassimilated following hierarchical growth and thus still be present today (e.g., Moore et al. 1999; Klypin et al. 1999; Davies et al. 2006). To date, however, the number of observed low-mass galaxies falls far short of these predictions. This is true locally, where only a handful of satellites surround the massive Local Group spirals (e.g., Mateo 1998), and is manifest in the faint end of the luminosity function that shows a slope more shallow than ACDM predictions (Blanton et al. 2001; Benson et al. 2003). This shortcoming of the ACDM model can be overcome either by preventing small DM halos from forming in the first place or by suppressing star formation so that they remain optically faint. The latter possibility implies a population of low-mass DM halos in which the baryon content remains optically dark but still visible chiefly through H i gas emission. The rarity of isolated extragalactic H i clouds lacking optical counterparts (Doyle et al. 2005) suggests that VIRGOHI 21, if truly massive, is a rare case in favor of this scenario.

An alternative to the dark galaxy interpretation for VIRGOHI 21 (Bekki et al. 2005; Haynes et al. 2007; Duc & Bournaud 2008) is that it is simply a part of an elongated H i–dominated tidal tail emanating from the nearby luminous galaxy NGC 4254 (M99). The tidal tail was caused either by a fly-by encounter with another (massive) galaxy (Vollmer et al. 2005) or by ram pressure stripping within the Virgo environment. Recent observations show the H i gas in the tail extends from NGC 4254, located \sim 120 \text{ kpc} to the south of VIRGOHI 21, to about 130 kpc beyond VIRGOHI 21 to the north (Haynes et al. 2007). The peculiar velocity structure in the vicinity of VIRGOHI 21 is, in this case, ascribed to projection effects on the streaming motions of the debris tail instead of to rotation within a gravitationally bound disk. In this scenario, the estimated H i mass is close to the total mass of the object; there is no massive halo accompanying VIRGOHI 21.

In § 2 we describe the Swift observations leading to upper limits of the X-ray emission from VIRGOHI 21, and in § 3 we provide our interpretation of the Swift nondetection. In this Letter we assume a distance to the source of D = 16.5 Mpc corresponding to the mean of the Virgo Cluster (Mei et al. 2007) and a scale of 4.9 kpc per arcminute.

2. SWIFT OBSERVATIONS OF VIRGOHI 21 AND DATA ANALYSIS

The VIRGOHI 21 field was observed by Swift on 2008 April 22 and 26 with the XRT operated in photon counting mode. The XRT has a very low detector background, which makes it especially suitable for observations of faint diffuse X-ray sources. These data are the first pointed X-ray observations of VIRGOHI 21.

The data were screened for bad pixels and other detector artifacts, and only photon grades 0–12 were included in the analysis. The screening resulted in 9.2 ks of clean data. In this analysis we considered photon energies in the 0.3–7 keV range, where the calibration of the XRT is better understood. The data reduction was performed using xselect and the FTOOLS, and the spectral analysis with XSPEC.

VIRGOHI 21 lies about 1 Mpc to the NW of the center of the Virgo Cluster at R.A. = 12^h17^m53.6^s decl. = +14^d45'25" (2000.0). The angular size of VIRGOHI 21, 3.5' \times 1.375', lies well within the 24' \times 24' field of view of the XRT (Cus-
A putative hot halo may be maintained in hydrostatic equilibrium by the gravitational potential of the galaxy. In this case, the H\textsc{i} feature was interpreted by Minchin et al. (2007) as a rotating disk, and the lower part as an H\textsc{i} bridge connecting VIRGOHI 21 with NGC 4254, located to the south and outside the Swift field of view.

As with normal galaxies, VIRGOHI 21 was expected to be a source of both diffuse and point-source X-ray emission. Even in the absence of stars, gas falling into a galaxy’s gravitational potential from the intergalactic medium should be heated to roughly the (X-ray emitting) virial temperature. In addition, accretion onto a central supermassive black hole from the gas reservoir in VIRGOHI 21, even at a fraction of the Bondi rate, should appear as a localized source of X-radiation although not necessarily optically bright. No X-ray emission associated with VIRGOHI 21 was detected. An unrelated weak (41 counts) pointlike source was detected near R.A. = 12\textdegree 17\textquoteleft 23\textquoteleft, δ = 14\textdegree 39\textquoteleft 29\textquoteleft represents the region from which we extracted the counts of the serendipitous source Swift XRT J121723+1439.5.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Fig. 1.—Swift XRT images of VIRGOHI 21, smoothed with a Gaussian kernel of σ = 7\arcmin. Gray contours are reproduced from the Minchin et al. (2007) H\textsc{i} observations with the Westerbork telescope. The black box represent the location of the putative H\textsc{i} rotating disk. The circle centered at R.A. = 12\textdegree 17\textquoteleft 23\textquoteleft, δ = 14\textdegree 39\textquoteleft 29\textquoteleft represents the region from which we extracted the counts of the serendipitous source Swift XRT J121723+1439.5.}
\end{figure}

\section{2.1. Diffuse X-Ray Emission}

In order to place upper limits to the diffuse soft X-ray emission from VIRGOHI 21, we accumulated X-ray photons from a 3.5\prime × 1.375\prime region located at the position of the putative H\textsc{i} disk (black box in Fig. 1). We detected a total of 8 counts in the 0.3–2 keV band, and no counts in the 2–7 keV band. We estimate the number of background counts, first by extracting the data from the entire field of view, excluding a region of enhanced emission to the south (Fig. 1) and regions close to the detector boundaries. The region included 337.3 square arcminutes. We found 623 counts in the 0.3–2 keV band and 319 counts in the 2–7 keV band. Ignoring the possibility that some of these events might be vignetted by the telescope one therefore expects in the region of interest at least 8.9 ± 0.4 counts in the soft band and 4.6 ± 0.3 in the hard band. We note that it is mildly interesting and somewhat improbable that no counts were measured in the hard band from the region containing VIRGOHI 21.

We use the soft X-ray band data in order to set upper limits as to source detection, since this is the band in which the X-ray emission from diffuse gas (and point sources) is expected. Since the measured background predicts at least a mean of 8.9 ± 0.4 counts and we detected 8 counts it is therefore evident that the VIRGOHI 21 region is not an X-ray emitter. To determine upper limits we increased the expected number of counts in the soft band by 10\% to 9.8 counts to account for the possibility that some of the measured background events arise from faint, unresolved X-ray sources. We determine 99\% confidence upper limits assuming 18 counts as detection.

\subsection{2.1.1. Uniform Distribution}

We assume that the H\textsc{i} disk is seen edge-on, and thus the emitting volume is \(V = \pi R^2 L\), where \(R = 1.75\prime\) and \(L = 1.375\prime\). We use an optically thin plasma of uniform density and solar abundance (\texttt{apec} in XSPEC), a Galactic H\textsc{i} column density of \(N_{\text{HI}} = 2.7 \times 10^{20} \text{cm}^{-2}\) (Dickey & Lockman 1990; Kalberla et al. 2005) with Morrison & McCammon (1983) cross sections (\texttt{wabs} in XSPEC), and calculate the emission measure required to achieve 8.2 source counts as a function of plasma temperature using XSPEC. The emission measure calculated by XSPEC is given by the model normalization, \(K\), as

\begin{equation}
K = \frac{10^{-14}}{4\pi D_c^2} \int n_e n_H dV, \quad (1)
\end{equation}

in which \(n_e\) and \(n_H\) are, respectively, the electron and hydrogen number density and \(D_c\) the angular size distance (for \(z \ll 1\)). From this, we calculate the gas density, and thus the gas mass. The results are shown in Figure 2, showing that these 9.2 ks Swift XRT observations set upper limits of the order of \(10^8 M_\odot\). These upper limits correspond to a flux of \(2.1 \times 10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\) in the 0.3–2 keV band.

\subsection{2.1.2. \(\beta\) Model Distribution}

A putative hot halo may be maintained in hydrostatic equilibrium by the gravitational potential of the galaxy. In this case,
We then estimate the upper limits to the gas mass by integration of the density profile,

$$M_{\text{gas}} = \mu_r \, m_H \int_0^R n_\alpha \left(1 + \frac{r^2}{r_c^2}\right)^{-3/2} \, 4\pi r^2 \, dr$$

$$= 4\pi \mu_r m_H n_\alpha r_c^2 I_2(R/r_c),$$

(4)

in which the $\beta$ model profile has led to the integral $I_2(R/r_c) = \int_0^R x^2(1 + x^2)^{-3/2} \, dx$. This integral is $I_2(n) = n - \arctan(n)$ for $\beta = 2/3$, and $I_2(n) = \ln \left[x + (1 + x^2)^{1/2}\right]$ for $\beta = 1/3$.

We estimate upper limits to the gas mass as function of plasma temperature using equations (3) and (4), using a fiducial value of the core radius of 0.5'. This model results in upper limits to the gas mass that are in the range of $M_{\text{gas}} = 4 \times 10^4$–$2 \times 10^8 M_\odot$. Upper limits to the gas mass are therefore similar to those obtained from the simple uniform density model of § 2.1.1.

2.2. Point-Source X-Ray Emission

We set upper limits to the luminosity of an unobserved point source anywhere within the 3.5' x 1.375' region of interest. The upper limit takes into account that there are 68 statistically independent Swift spatial resolution elements within this region, given that the half-power diameter of the XRT point-spread function at 1.5 keV is 18'. The measured background per 18' diameter spatial resolution element is 0.131, or 0.144 using a +10% allowance for vignetting. Thus, considering the Poisson distribution with a mean of 0.144 and a total of 4 counts, there is a probability of only $1.6 \times 10^{-3}$ of measuring 4 or more counts in just one of these resolution elements. Of course we would have been happy to measure 4 or more counts in any one of the 68 elements so the joint probability is correspondingly larger. Thus, we can state with approximately 99.9% confidence that we have not detected a source of 4 counts or brighter from this region.

We consider a power-law emission model with photon index $\Gamma = 2.0$ and determine the upper limits to the source luminosity as function of the absorbing H I column density using XSPEC. The upper limits are shown in Figure 2, and are in the $L = 3 \times 10^{38}–10^{40}$ ergs s$^{-1}$ range. This upper limit corresponds to a flux of $8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.3–2 keV band.

2.3. UV and IR Emission

For completeness, we also analyzed extant non-X-ray images of VIRGOHI 21.

Swift UVOT images using the UVM2 filter (effective wavelength 2231 Å) were obtained concurrently with the XRT data. No sources were detected within the angular extent of VIRGOHI 21. The FTOOLS utility uvotsource was used to estimate a limiting magnitude for the UV emission from the 3.5' x 1.375' region enclosing VIRGOHI 21. This limit does not improve our estimates of the upper limit to the mass of diffuse hot gas nor to the flux from a point source as estimated above from the X-ray data.

We also analyzed archival Spitzer data (program ID 30725) which included all four IRAC and three MIPS spectral bands. Again, no extended emission was detected within the H I extent.
of VIRGOHI 21. We estimate an upper limit to the mass of dust associated with VIRGOHI 21 to be $10^4$–$10^6 M_\odot$ depending on the dust temperature assumed.

3. DISCUSSION AND CONCLUSIONS

A search for X-ray emission from the H\textsc{i} line source VIRGOHI 21 using the Swift XRT obtained only upper limits. The nondetection indicates that any diffuse X-ray-emitting gas at $kT = 0.1$–1 keV must be less massive than $4 \times 10^{-2} - 2 \times 10^6 M_\odot$, depending on the gas temperature and its spatial distribution. Given that the Swift XRT detector has no effective area approximately below 0.1 keV, it is possible that significant amounts of gas at subvirial temperature have gone undetected. Instead, our expectation that VIRGOHI 21 should be a source like VIRGOHI 21 (White & Frenk 1991). We would expect a gas virial temperature of approximately 0.4 keV based on the observed kinematics of VIRGOHI 21 (from Minchin et al. 2007) and thus our best guess to the amount of hot gas associated with VIRGOHI 21 is $\lesssim 5 \times 10^7 M_\odot$. Scaling from simulations of gas infall onto stable disk galaxies (Benson et al. 2000; Toft et al. 2002), the X-ray luminosity of this gas should be up to $5 \times 10^{38}$ ergs s$^{-1}$ for rotation speeds similar to that of VIRGOHI 21.

The above estimates are based on the assumption of an isolated “quiescent” massive galaxy accreting slowly (i.e., with a long cooling time) from the surrounding intergalactic medium. In the particular case of VIRGOHI 21, in contrast, a considerable gas reservoir exists within the tidal tail emanating from NGC 4254 that should lead to a relatively high gas accretion rate and hence high X-ray luminosity. Furthermore, turbulence and shocks following the interaction between VIRGOHI 21 and NGC 4254 would very likely heat some portion of the disk H\textsc{i} gas component of VIRGOHI 21 to X-ray-emitting temperatures. We therefore consider the above estimates to be minimal expectations. Of course, any prediction of the amount of hot gas or its luminosity will scale with the dynamical mass of the accreting object.

The observed upper limits reported here, therefore, show that the extreme object VIRGOHI 21 is not an extreme X-ray object (in the sense of a high $f_x/f_o$) nor has it accreted very much gas from its surroundings during its lifetime.

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