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A VLA SEARCH FOR NEUTRAL HYDROGEN IN COOLING FLOW CLUSTERS

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ABSTRACT

We present a VLA search for neutral hydrogen in three clusters, which are considered to be prime examples of so-called cooling flow clusters: Virgo (Virgo A), Abell 2199 (3C 338), and Abell 780 (Hydra A). We looked for H I in absorption against the central radio sources with a velocity coverage $\sim$2600 km s^{-1} and with a velocity resolution $\sim$87 km s^{-1}. We do not detect a spatially extended distribution of cold clouds. Our 3 σ optical depth limits are 0.0005 over a typical velocity range of 500 km s^{-1}. Assuming the currently popular cooling flow scenarios in which the distribution of the cold gas can be characterized by a core radius of $\sim$100 kpc, our results place an upper limit of 1.2×10^{10} $M_{\odot}$ to the mass of neutral hydrogen in such a flow for an assumed spin temperature of 100 K. This limit is a factor of 30 below what is expected from the *Einstein* Solid State Spectrometer observations of cooling flow clusters and is 1–2 orders of magnitude below what is expected from the cooling flow models. The expected large amount of H I is unlikely to exist in these clusters even as optically thick clouds unless their spin temperature is less than 10 K and/or their covering factor is much less than 1. We discuss some physical conditions in which the expected large amounts of H I could have escaped detection.

We do, however, find H I absorption against the core of Hydra A. This line is narrow ($\sim$50 km s^{-1}) and is not seen against the extended radio lobes. The properties of this absorption system are similar to those seen in some other cooling flow clusters and in isolated radio galaxies. We also detect a spiral galaxy in A 2199 with a total mass of 1.8×10^9 $M_{\odot}$.

Despite this detection of what might be a small H I cloud near the systemic velocity of the core of Hydra A, we do place stringent limits on the existence of such clouds anywhere within the primary beam. The upper limit to H I emission from such clouds ranges from 10^7 to 10^9 $M_{\odot}$.

Subject headings: cooling flows — galaxies: clustering — galaxies: clusters: individual (Virgo A, Abell 780, Abell 2199) — intergalactic medium — radio lines: general

1. INTRODUCTION

X-ray observations of clusters of galaxies have revealed the presence of large amounts of intracluster gas. This X-ray emission is due to thermal bremsstrahlung from a plasma with $T_e \sim 10^7$–10^8 K and $n_e \sim 10^{-3}$ to 10^{-2} cm^{-3}. The amount of X-ray–emitting gas is $\sim 10^{14}$ $M_{\odot}$ ($\sim$10% of the virial mass of the cluster) contained within 1–2 Mpc. The luminosity in X-rays is in the range $\sim 10^{43}$–10^{45} ergs s^{-1} (e.g., Fabian, Nulsen, & Canizares 1991, Sarazin 1986, and references therein). Detailed spatial and spectral studies of the surface brightness of the clusters based on the *Einstein* observations have led to the conclusion that the density of the intracluster gas increases ($10^{-3} \rightarrow 10^{-2}$ cm^{-3}) and its temperature decreases ($10^8 \rightarrow 10^7$ K) toward the centers of many clusters (Jones & Forman 1984; Arnaud 1988; Canizares et al. 1979; Canizares 1981; Canizares, Markert, & Donahue 1988; Mushotzky et al. 1981; Mushotzky & Szymkowiak 1988; Lea, Mushotzky, & Holt 1982).

The presence of cooler ($\sim 10^7$ K) gas toward the cluster cores has been explained in cooling flow scenarios (Fabian et al. 1991). Assuming that the gas is in hydrostatic equilibrium and ignoring energy inputs, a quasi–steady-state solution is derived. The observed density of the intracluster gas increases toward the cluster core. Consequently the gas in the core can cool considerably over the age of the cluster. The density in the core has to further increase to support the weight of the overlying gas. The only way this can happen is by the gas flowing inward leading to the cooling flows. This model along with the X-ray observations imply that $\sim 10^{11}$–10^{12} $M_{\odot}$ of gas condenses out of the hot phase over the lifetime of the cluster. The observed X-ray surface brightness distribution and the intensity of the Fe XVII line appear to indicate that the cooling gas does not all flow into the cluster center but is distributed over a region whose radius $r_{\rm cool} \sim 100$ kpc with a small volume filling factor. This consideration has led to the view that the condensing gas presumably forms blobs (Canizares et al. 1988; Fabian et al. 1991). The ultimate fate of this cooling gas is unclear. It has been proposed that this gas might end up in the form of small (< 1 pc) optically thick H I clouds or turn into low-mass (< 1 $M_{\odot}$) stars (Loewenstein & Fabian 1990; Ferland, Fabian, & Johnstone 1994; Fabian et al. 1991). There is some evidence for star formation in cooling flow clusters (O'Connell & McNamara 1988; Johnstone, Fabian, & Nulsen 1987; Johnstone & Fabian 1989). More recently, the *Einstein Observatory* Solid State Spectrometer (SSS) has detected significant excess absorption in the X-ray spectra of 12 clusters of galaxies (White et al. 1991). This absorption must arise in a gas at temperatures $\leq 10^{6.4}$ K. The average hydrogen column density of the absorbing gas corresponds to $\sim 10^{21}$ cm^{-2}. The observations imply a covering factor $\sim$1 within the cooling radius $\sim$100 kpc. This would imply a total mass $\sim 3 \times 10^{11}$ $M_{\odot}$.

Once the gas cools below $\sim 10^6$ K it is expected to cool further very quickly. There are no detections of a uniformly distributed gas in the temperature range 10^6–10^4 K. It appears, however, that the present detection limits in the UV and optical cannot rule out the presence of such a gas distributed

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over r_{cool} (Fabian 1992; Johnstone et al. 1987). There is some evidence for warm gas in the centers of cooling flow clusters from optical observations. The inferred values are $n_e \sim 100$ cm^{-3}, $T_e \sim 10^4$ K, and mass $\sim 10^5$–10^7 $M_\odot$. Detailed studies of these nebulosities have concluded that the connection of this gas to the cooling flow is unclear (Heckman et al. 1989; Baum 1992).

If most of the gas has cooled well below 10^4 K, then large quantities of neutral hydrogen (H I), or even molecular hydrogen (H_2), might be expected. If the cold gas indeed exists in the form of H I then we should expect to see it in absorption against the strong continuum radio sources that usually reside in these clusters. Such attempts have been made in the past (Crane, van der Hulst, & Haschick 1982; Jaffe, de Bruyn, & Sijbring 1988; Jaffe 1990; Jaffe 1991, 1992; McNamara, Bregman, & O'Connell 1990), and 21 cm absorption has so far been detected in four clusters: Perseus, A0335+096, MKW 3s, and Virgo A. The amount of H I inferred to be present in Perseus A is $\sim 5 \times 10^9$ $M_\odot$. The mass of H I in the other three clusters implied by the emission limits is $\leq 10^9$ $M_\odot$ which is much less than that implied by the X-ray spectra. In many other clusters H I is not detected at this level.

Searches for molecular gas in cooling flow clusters have also been made with a detection of CO only in Perseus A (Mirabel, Sanders, & Kazes 1989; Lazareff et al. 1989). The amount of H_2 gas is estimated to be $\sim 3 \times 10^9$ $M_\odot$, assuming the Galactic CO to H_2 conversion. Searches in other clusters have only resulted in upper limits $\sim 10^9$ $M_\odot$ (Jaffe 1987; Bregman & Hogg 1988; Grabelsky & Ulmer 1990; O'Dea et al. 1994; Antonucci & Barvainis 1994; McNamara & Jaffe 1994).

It is quite surprising that the detected cold gas masses and upper limits are at least a factor of 100 lower than that required to explain the X-ray observations. Since the X-ray absorption requires a fairly large covering factor, this gas must be widely distributed, but could be patchy. Although the expected velocity widths are large, the actual values are somewhat uncertain. If the cold gas were to have the same velocity spread as the galaxies in the cluster, the widths would be ~ 500–1000 km s^{-1}. It has also been argued that the cold gas survives the harsh atmosphere of the intracluster medium by comoving with the hotter, turbulent gas (Loewenstein & Fabian 1990) leading to velocity widths of the cold gas in excess of 100 km s^{-1}. The only velocity widths that have been measured are those of the 10^4 K gas, which can be detected in optical emission lines from the centers of many cooling flow clusters. The measured widths are 100–1000 km s^{-1} (Hu, Cowie, & Wang 1985; Johnstone et al. 1987; Heckman et al. 1989). Like this 10^4 K gas, the velocity width of the cold gas could be in the range of 100–1000 km s^{-1}. The motivation for the present observations was to search for such spatially extended, wide H I absorption lines. The present observations are well suited to detect lines as wide as 500 km s^{-1}. Wider lines ~ 1000 km s^{-1} could be missed in the present observations as in most of the earlier attempts at detecting cold gas in cooling flow clusters. It is quite likely that the wide (~ 500 km s^{-1}) H I absorption line detected against the nuclear source of Perseus A (Jaffe 1990) is one such example, although the evidence for its spatial extent is very weak.

In this paper we describe our attempts at detecting neutral hydrogen in absorption and/or emission in three of the cooling flow clusters. We observed the radio sources Virgo A, 3C 338, and Hydra A in the clusters Virgo, A2199, and A780. Virgo and A2199 are the best detections of excess absorption in the X-rays by White et al. (1991). All three clusters have bright ($T_b \sim 10^3$–10^4 K), and extended (over 1′–2′) radio continuum sources making it possible to explore the spatial distribution of the H I gas. The expected column density of neutral hydrogen ($N_H \sim 10^{21}$ cm^{-2}), if cold ($< T_b$), should be detectable as absorption of the radio continuum. In this paper we assume $H_o = 75$ km s^{-1} Mpc^{-1}.

2. OBSERVATIONS AND DATA PROCESSING

The observations were carried out during 1993 March–April using the Very Large Array (VLA). Details of the observations are indicated in Table 1. All the observations were carried out while the VLA was in its B configuration giving an angular resolution $\sim 6''$. A description of the VLA is given by Napier, Thompson, & Ekers (1983). We used a bandwidth of 12.5 MHz, 32 channels, and on-line Hanning smoothing resulting in a frequency resolution ~ 390 kHz. Our total velocity coverage was ~ 2600 km s^{-1} with a velocity resolution ~ 87 km s^{-1}. For each cluster the band was centered at the systemic velocity of the radio galaxy (using the optical definition and heliocentric velocity). The systemic velocities are listed in Table 1. Since this experiment was aimed at detecting absorption, the integration time per cluster was determined by the strength of the central radio source.

The most important aspect of these observations was the bandpass calibration since the primary motivation was to detect weak, broad absorption toward strong continuum sources. At very low levels (a fraction of a percent) a standing wave ripple can be seen in the bandpasses of the VLA (Carilli 1991). The variation of this ripple with time and/or position limits high spectral dynamic range observations. To achieve the required spectral dynamic range we interleaved our observations with an observation of a bandpass calibrator every 20 minutes, sufficient to calibrate out the time variability (van Gorkom et al. 1993). To minimize changes with position, we selected bandpass calibrators as close to the clusters as possible, all within 10° of the central cluster source. The amplitude and phase calibration was done once every hour. The absolute

TABLE 1

OBSERVATIONS

Radio Source	V_{sys} (km s^{-1})	Distance (Mpc)	Field Center R.A.(1950)	Field Center Decl.(1950)	Synthesized Beam			Observing Frequency (MHz)	Integration Time (hr)
Virgo A	1282	17	$12^h28^m17^s.569$	+12°40′01″.71	5″.59	5″.04	−0°.82	1414.4	5.5
3C 338	9150	122	16 26 55.350	+39 39 36.40	6.54	5.54	−67.82	1378.4	14.25
Hydra A	16200	216	09 15 41.450	−11 53 08.30	7.38	5.46	15.61	1347.5	4

NOTES.—The radio sources Virgo A, 3C 338, and Hydra A are associated with the Virgo, A2199, and A780 clusters, respectively. The velocities are from Owen et al. 1994. $H_o = 75$ km s^{-1} Mpc^{-1}.

flux densities were determined using the observations of 3C 48 and 3C 286.

The data were analyzed using the Astronomical Image Processing System developed by the NRAO. The channel 0 of the spectral line data contains the average visibility of the inner 75% of the frequency bandwidth. After amplitude and phase calibration, these data were used to construct a continuum image of the field. Several iterations of self-calibration were necessary to achieve a dynamic range $\sim 1{:}2000$ in the continuum images. In each case the amplitude and phase solutions from the self-calibration and from the calibrators were applied to the spectral line data. The spectral line data were corrected for the instrumental frequency response by using the response of the bandpass calibrator nearest to it in time. The continuum was subtracted from the spectral line data of each of the clusters by performing a linear fit to the visibilities over the inner 75% of the band (Cornwell, Uson, & Haddad 1992), usually between channels 5 and 25. Spectral line cubes were made using both uniform and natural weighting. The rms noise per channel in these cubes was within a factor of 1.5 of the theoretically expected values. Although the continuum images containing strong sources do not reach the thermal noise and are dynamic range limited due to calibration errors, the visibility based continuum subtraction removes some of these errors from the spectral line data. The cubes were examined by eye for any spectral features. In addition, the cubes were smoothed in frequency to search for broad lines (~ 1000 km s^{-1}). A Gaussian with a full width at half-maximum of 6 channels (~ 500 km s^{-1}) was used for smoothing the spectral cubes. The spectral cubes were also convolved to different spatial resolutions to look for possible emission and/or absorption features at various angular scales.

We show in Figure 1 (broken line) the result of dividing two successive band passes obtained on the source 0834−196

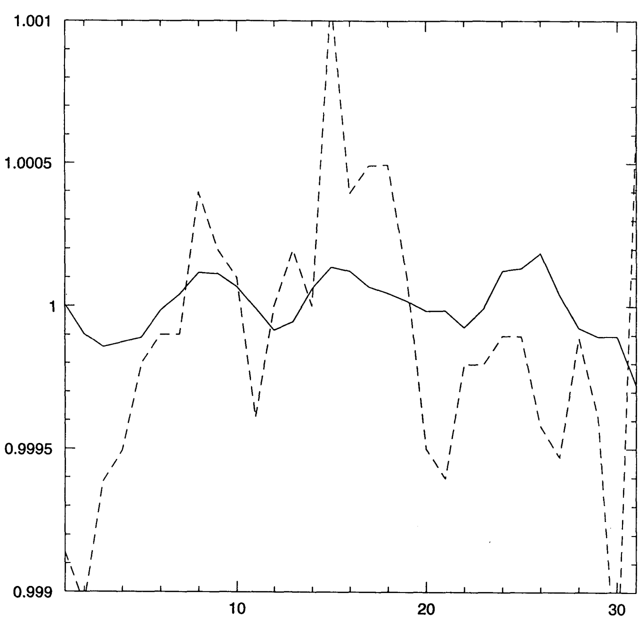

FIG. 1.—Residuals across the bandwidth of 12.5 MHz. The broken line is the result of dividing two successive bandpasses obtained with the calibrator 0834−196. The peak-to-peak deflection corresponds to an rms ~ 1 part in 2000. This very nearly is the signal-to-noise ratio expected per channel in 5 min for a 5 Jy source. All such successive divisions obtained during the observation of Hydra A (for which 0834−196 was the bandpass calibrator) were averaged to produce the solid line. This implies that the current bandpasss calibration allows detections of 1 in 3000.

during the observations. The source 0834−196 was used as a bandpass calibrator for observing the A780 cluster containing the radio source Hydra A. The residual has very little systematics in it and is consistent with that expected on the basis of thermal noise for an integration time of 5 minutes and the strength of the source. Figure 1 also shows (solid line) the average of such successive divisions of band passes during the observations of Hydra A. It is clear from this that the residuals from the bandpass calibration do not exceed 1 in 3000 (peak to peak) of the continuum. This spectral dynamic range was also achieved with the other bandpass calibrators. If the instrumental response does not change from the bandpass calibrator to the cluster, we should be able to detect any spectral line feature that is greater than 1 in 3000 of the continuum.

3. RESULTS

In Figure 2 we show the continuum images of the three cluster sources. The areas covered by Virgo A, 3C 338, and Hydra A are ~ 18.5 kpc^2 ($90'' \times 30''$), 1170 kpc^2 ($110'' \times 30''$), and 3885 kpc^2 ($120'' \times 30''$). We detect H I absorption against the core of Hydra A and as well as H I emission from a spiral galaxy close to the center of Abell 2199. However, we do not detect the expected broad and extended H I absorption against any of the cluster sources. We do not confirm the preliminary reports of a detection of H I in absorption and emission toward Virgo A (Jaffe 1992). First we shall discuss the upper limits to such broad absorption features, and then we discuss the detections.

We present optical depth limits (τ_p) for a single (~ 87 km s^{-1}) channel per synthesized beam ($6''$), and the limit on optical depth obtained after averaging over the entire radio source and smoothing in frequency over 500 km s^{-1} (τ_{avg}). The limit on optical depth per synthesized beam is useful if there is structure in the absorbing gas on scales of a few arcseconds. However, if the absorbing gas is uniformly distributed across the continuum source, then it is reasonable to obtain an average optical depth (τ_{avg}). The average optical depth is estimated by averaging the optical depth spectra obtained along different (but, independent) lines of sight to the continuum source, where each spectrum is weighted by the square of the continuum flux density at that point. In Figures 3, 4, and 5 we show full resolution spectra for Virgo A, 3C 338 (cluster A2199), and Hydra A (cluster A780) obtained at three local maxima in the continuum images, which are indicated with a cross in Figure 2. The limits on optical depth obtained from these spectra are indicated (τ_p) in Table 2. The spectra obtained by smoothing in frequency and averaging over the source (excluding the core in the case of Hydra A) are shown in Figure 6 for the three clusters. The limits on optical depth obtained from these spectra are also indicated (τ_{avg}) in Table 2. These values correspond to the peak-to-peak deflections observed (Fig. 6). As can be seen from this figure, we reach almost the same optical depth limit in all cases. These optical depth limits can be used to set an upper limit on the mean H I column density per synthesized beam or averaged over the source, assuming a value for the spin temperature and a velocity range over which the absorption takes place. The H I column density can be calculated using the relation

$$N_H = 1.82 \times 10^{18} \tau T_s \Delta v \text{ cm}^{-2} , \qquad (1)$$

where τ is the optical depth, T_s is the spin temperature of the H I gas in K, and Δv is the assumed width of the line in km s^{-1}

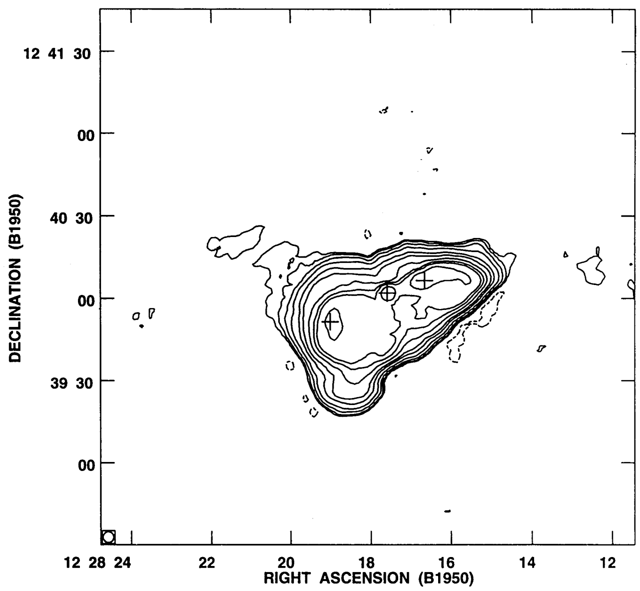

FIG. 2*a*

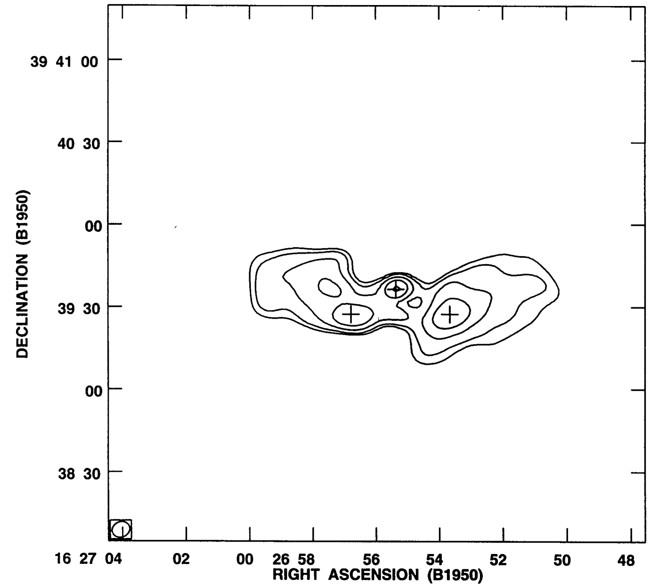

FIG. 2*b*

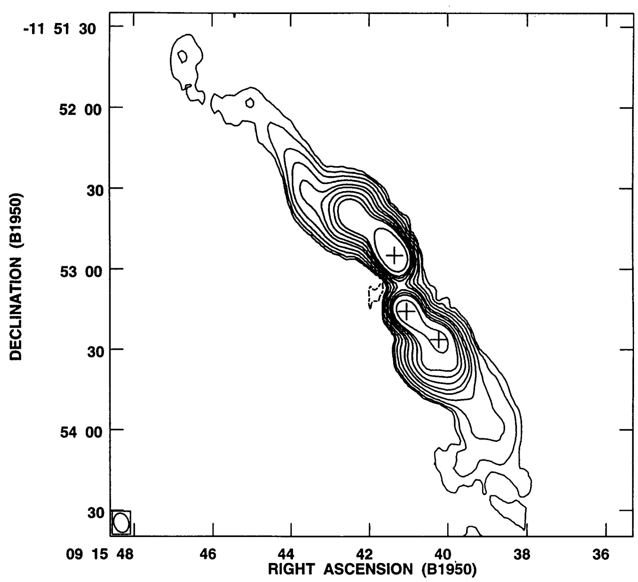

FIG. 2*c*

FIG. 2.—Continuum images of the radio sources from the present observations. Panels (*a*), (*b*), and (*c*) correspond to Virgo A, 3C 338, and Hydra A, respectively. The contours are at −25, −15, 15, 25, 50, 100, 200, 300, 500, 750, 1000, and 2000 mJy beam^{-1}. The crosses mark the positions of three local maxima. The spectra obtained at these positions are shown in Figs. 3, 4, and 5 for the three sources.

(Spitzer 1978). The mass contained within an area A corresponding to this column density can then be estimated using

$$M_{\rm H} = 8.0 \times 10^5 N_{\rm H20} A \; M_\odot \, , \qquad (2)$$

where $N_{\rm H20}$ is the H I column density in units of 10^{20} cm^{-2}, and A is the area in units of kpc^2. In Table 2 we list the 3 σ column density limits assuming $T_s = 100$ K and $\Delta v = 500$ km s^{-1}. We also list the corresponding upper limits to the total absorbing gas in front of the individual sources ($M_{\rm H}^s$) estimated using the areas of the sources. If the absorbing H I gas is uniformly distributed within the cooling radius as is required, we can set an upper limit to the total mass of this gas by extrapolating our limit across the source to the cooling radius (assumed to be 100 kpc). These limits are also listed in Table 2 ($M_{\rm H}$).

Although we do not detect any broad, spatially extended H I absorption features, we do detect H I in these observations. In Hydra A we detect a narrow (<87 km s^{-1}) absorption line against the core (Fig. 7), a line first reported by G. B. Taylor (1993, private communication), who detected the line in a VLA D-array observation. The absorption occurs at a heliocentric velocity of 16,291 km s^{-1} (optical definition; no relativistic correction applied) which is close to the sytemic velocity of the galaxy (Owen, Ledlow, & Keel 1994; Ekers & Simkin 1983) of

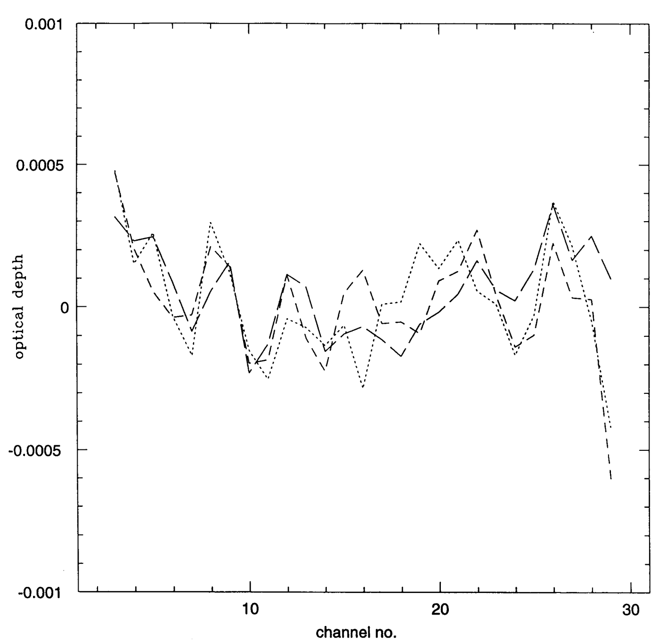

FIG. 3.—Spectra toward the crosses in Virgo A. Velocity resolution is 83.1 km s^{-1}. Channel 16 corresponds to $V_{\rm sys}$ in Table 1.

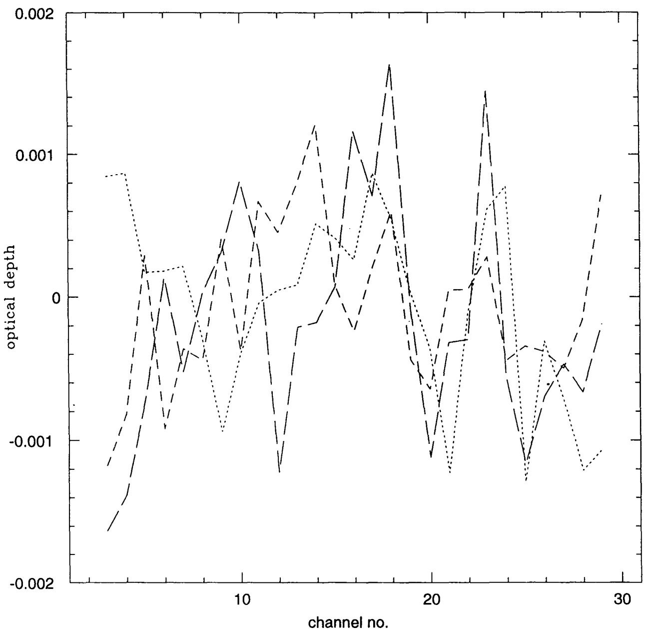

FIG. 4.—Spectra toward the crosses in 3C 338. Velocity resolution is 87.6 km s^{-1}.

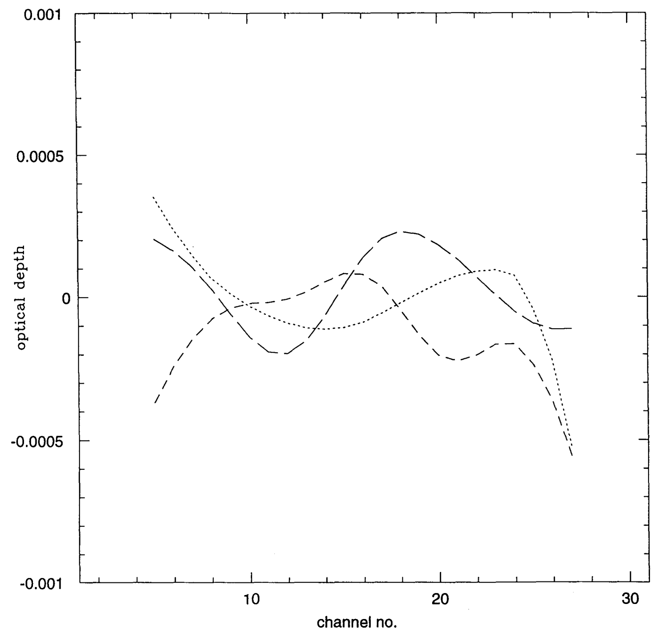

FIG. 6.—Average spectra toward the three sources observed. The original data were smoothed in frequency with a Gaussian ~500 km s^{-1} (FWHM). A single profile for each source was obtained by suitably averaging the optical depth over the source. Dotted, short-dashed, and long-dashed lines correspond to the sources Virgo A, 3C 338, and Hydra A, respectively.

16,200 km s^{-1}. The observed optical depth of the line is 0.07. The line is not well resolved in velocity, although it is detected in an adjacent channel. Its observed full width at half-maximum is less than the width of 1 channel (~87 km s^{-1}). Based on this the intrinsic line width is not expected to be larger than ~50 km s^{-1}. For an assumed spin temperature of 100 K and a line width of 50 km s^{-1}, the absorption corresponds to a column density of H I of 6.4×10^{20} cm^{-2}. Since the absorption line is relatively narrow (~50 km s^{-1}), and not spatially extended (we do not see it against the extended radio lobes), it is quite different from what is predicted by cooling flow models. However, it is similar to what has been seen in some other cooling flow clusters (McNamara et al. 1990) and looks strikingly similar to absorption features seen in more isolated radio galaxies (van Gorkom et al. 1989).

For each of the clusters we imaged the full primary beam (1° × 1°) to search for H I in emission. The only detection is a spiral galaxy in Abell 2199 at a projected distance of only 104

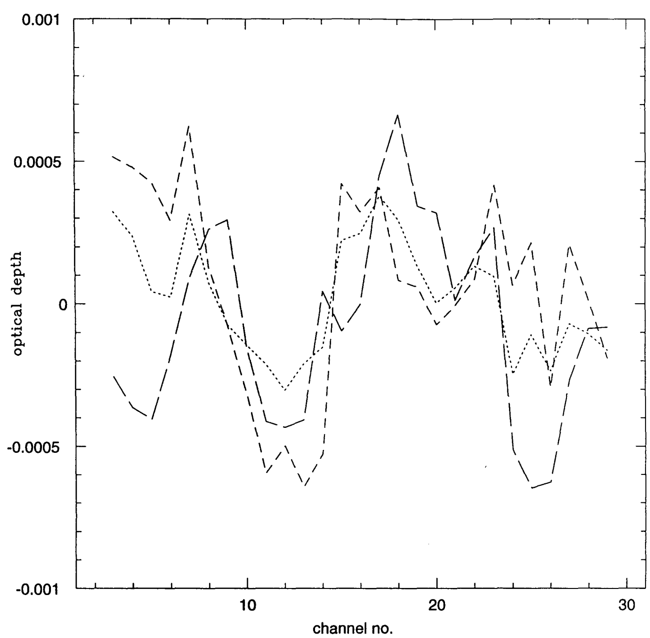

FIG. 5.—Spectra toward the crosses in Hydra A. Velocity resolution is 91.6 km s^{-1}.

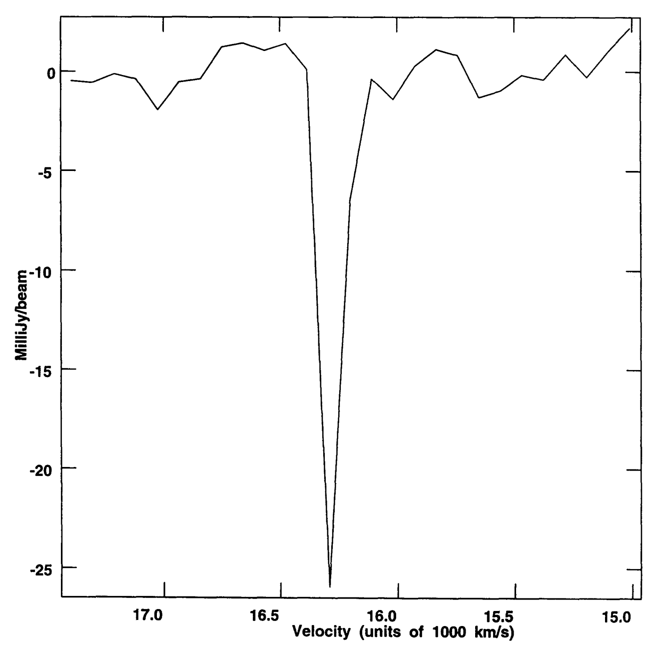

FIG. 7.—H I absorption toward the core of Hydra A. The spectrum is at $\alpha(1950)$ $09^h15^m41^s.246$ and $\delta(1950)$ $-11°53'05''.30$. The continuum flux density at this position is 371.8 mJy $beam^{-1}$. The velocity is optical definition, and heliocentric with no relativistic correction.

TABLE 2

ESTIMATED PARAMETERS OF CLUSTERS

Radio Source	RMS/Channel (m Jy beam^{-1})		Peak Flux (Jy beam^{-1})	τ_p (10^{-4})	$N_{H,p}$ (10^{18} cm^{-2})	τ_{avg} (10^{-4})	N_H (10^{19} cm^{-2})	M^s_H ($10^7\ M_\odot$)	M_H ($10^{10}\ M_\odot$)	M^e_H ($10^7\ M_\odot$)
Virgo A	0.42	0.21	6.9	<2	<3.0	<5	<5	<0.7	<1.2	<0.9
3C 338	0.13	0.04	0.22	<10	<15.8	<5	<5	<47	<1.2	<14
Hydra A	0.42	0.20	7.5	<5	<8.3	<5	<5	<155	<1.2	<139

NOTES.—The two entries under rms/channel correspond to unsmoothed and smoothed data, respectively. Smoothing was done in frequency with a Gaussian of FWHM ~500 km s^{-1}. τ_p estimated from spectra toward peaks (Figs. 3, 4, and 5). τ_{avg} estimated from averaging over the source and frequency (Fig. 6). Both are 3 σ values. $N_{H,p}$ and N_H are 3 σ limits estimated using τ_p and τ_{avg} for an assumed spin temperature of 100 K and a line width of 1 channel (~87 km s^{-1}) and 500 km s^{-1}, respectively. M^s_H is the mass in front of the source estimated using N_H and the area of the source. M_H is the mass within r_{cool} = 100 kpc estimated using N_H. M^e_H is the 3 σ mass limit within the synthesized beam for an assumed line width of 100 km s^{-1} estimated using the rms for the unsmoothed data.

kpc (176″) from the cluster center. In Figure 8 we show the total hydrogen image. H I is detected in 3 channels centered at 8712 km s^{-1}, which is close to the systemic velocity of the cluster. The total hydrogen mass is $1.8 \times 10^9\ M_\odot$. The H I does not seem to extend beyond the optical disk, which is not surprising if the galaxy is indeed located close to the center of the cluster (Cayatte et al. 1990). The present observations are not particularly sensitive to H I emission, and it does not come as a surprise that more galaxies were not detected—even more so since in Virgo there are no galaxies within a projected distance of 1° of M87 and the cluster associated with Hydra A is more distant, making the upper limits even less interesting. Due to the low filling factor of the B configuration of the VLA our surface brightness sensitivity is poor. In Table 2 we list 3 σ upper limits to the total H I mass per beam, (M^e_H), for a line width of 100 km s^{-1} for each of the three clusters.

4. DISCUSSION

4.1. *The Apparent Absence of Uniformly Distributed Cold Gas*

The primary motivation for our observations was to search for the uniformly distributed large amounts of cold gas as inferred from *Einstein* SSS spectroscopy (White et al. 1991). The column densities for the absorbing gas inferred from those observations are 10^{21} cm^{-2}. This estimate is based on X-ray analyses which assumed a foreground absorbing screen. If the absorbing and emitting gas are mixed then that fraction of the cold absorbing gas which is behind the hotter X-ray–emitting gas will not contribute to X-ray absorption. However, this cold gas will still be detected in H I absorption since it is in front of the radio continuum source. Thus the X-ray inferred column densities for the absorbing gas are lower limits. Our limits on the optical depth to H I absorption in the three clusters result in an upper limit (3 σ) to the column density of

$$N_H < 5 \times 10^{19} T_{100} \Delta v_{500}\ \mathrm{cm}^{-2}\ , \tag{3}$$

where T_{100} is the spin temperature of H I gas in units of 100 K, and Δv_{500} is the width of the line in units of 500 km s^{-1}. For $T_{100} = 1$, and $\Delta v_{500} = 1$ the column density of H I is a factor of 30 below that expected from the SSS observations. If the assumed spin temperature is increased from 100 to 3000 K the limits on column density will go up by the required factor of 30. Our observations by themselves cannot rule out this possibility. This gas, however, would be optically thin and should in principle be detectable in emission. The most sensitive search for H I emission from cooling flow clusters by McNamara et al. (1990) sets typical upper limits to the total amount of H I of $6 \times 10^9\ M_\odot$, two orders of magnitude below the predicted values. These limits are for an assumed line width of 300 km s^{-1}. If the H I gas has a velocity dispersion similar to that of the optical emission line gas in the clusters one can expect line widths ~500–1000 km s^{-1}. Very broad (~1000 km s^{-1}) and weak emission lines might have escaped detection in the existing single dish observations due to a combination of standing wave problems, interference, and confusion. Although the existing emission measurements cannot rule out, it is unlikely that hot ($T_s > 3000$ K) H I gas with widths ~1000 km s^{-1} exists in clusters.

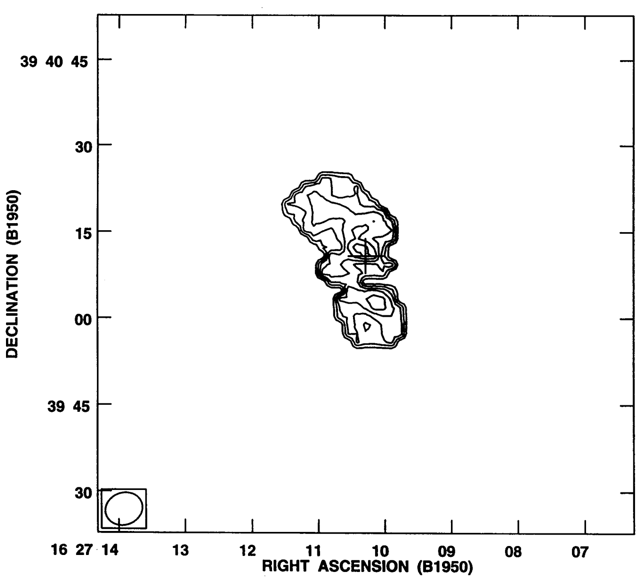

FIG. 8.—Total hydrogen map of the galaxy detected in A2199. The contours are at 10, 20, 30, 40, 50, and 60 Jy beam^{-1} m s^{-1}. The cross marks the position of the maximum of the optical image.

An alternative and intriguing possibility is that the clouds are very cold ($\ll 100$ K) and very small ($\ll 1$ pc) (Loewenstein & Fabian 1990). The low spin temperature makes these clouds optically thick ($\tau \gg 1$) and thus renders them unobservable in H I emission experiments. Despite the large intrinsic optical depths, the small velocity widths resulting from the low temperature and the small sizes of these clouds seriously dilute the observed optical depth thus making it hard to detect these clouds even in absorption experiments. Nevertheless our limits on the optical depth seriously constrain the available parameter space for such clouds. The intrinsic width of the 21 cm absorption lines due to these clouds is $v_{int} \sim 0.7 T_{10}^{0.5}$ km s^{-1} where T_{10} is the spin temperature of these clouds in units of 10 K. If these clouds have a velocity dispersion characteristic of the turbulence in the intracluster gas (v_{tur}), the absorption from such a system of clouds will be reduced by v_{int}/v_{tur}. So we can expect the observed optical depth from such a system of clouds to be $\tau_{obs} \sim v_{int} v_{tur}^{-1} f$, where f is the covering factor of these clouds. This relation can be inverted to constrain the covering factor of such clouds. The covering factor is

$$f \sim 714 \tau_{obs} T_{10}^{-0.5} v_{500} , \quad (4)$$

where v_{500} is the velocity of the clouds in units of 500 km s^{-1}. In the present observations $\tau_{obs} < 0.0005$ implying that the absorption from such a system of clouds ($T_s = 10$ K; $v_{tur} = 500$ km s^{-1}) could not have been missed unless their covering factor were less than 0.36. Due to their large optical depth, only about 1% of the H I emission would escape from the clouds reconciling the current emission limits ($\sim 10^9$ $M_\odot$) with the amounts expected ($\sim 10^{11}$ $M_\odot$) in the cooling flow scenarios. The present observations along with the existing emission experiments rule out the existence of large amounts ($\sim 10^{11}$ $M_\odot$) of H I unless the spin temperature is less than 10 K and/or the covering factor is much less than 1. The SSS results on the other hand require a filling factor ~ 1 for the cold clouds to explain their observations.

We have ruled out the existence of large amount of H I within a wide range of physical parameters. In a recent analyses of the physical conditions within dense cold clouds in cooling flows Ferland et al. (1994) have concluded that at temperatures like 10 K the cloud is significantly molecular throughout much of its core. This could explain the nondetections of H I. Searches for molecular gas in cooling flow clusters have also been made with a detection of CO only in Perseus A (Mirabel et al. 1989; Lazareff et al. 1989). The amount of H_2 gas in Perseus A is estimated to be $\sim 3 \times 10^9$ $M_\odot$, assuming the Galactic CO to H_2 conversion. Searches in other clusters have only resulted in upper limits $\sim 10^9$ $M_\odot$ (Jaffe 1987; Bregman & Hogg 1988; Grabelsky & Ulmer 1990; O'Dea et al. 1994; Antonucci & Barvainis 1994; McNamara & Jaffe 1994). These observations include the three clusters discussed in our paper. Thus the upper limits to the amount of molecular gas are also several orders of magnitude below what is required to explain the X-ray absorption.

Another possibility is that the H I column densities derived for the X-ray–absorbing gas as observed by the SSS have been overestimated. There are three possible reasons. (1) There might be an overabundance of oxygen. The main absorber in the SSS band (0.6–4.5 keV) is oxygen. Assuming cosmic abundance, the column density of oxygen may be translated to obtain that of hydrogen. If oxygen is overabundant in the intracluster gas, then, the amount of hydrogen present will be less by the corresponding factor. In fact, in the case of Virgo A, there are indications that oxygen may be overabundant by a factor 3–5 relative to solar values (Canizares et al. 1982). Even then, the present upper limits on the column density of H I are a factor 6–10 below that required by the SSS observations. (2) There might be some calibration uncertainties associated with the SSS (Tsai 1992). Although this might be true, more recent observations by *ROSAT* and *ASCA* seem to confirm the results of excess absorption as seen by the SSS (Allen et al. 1993). (3) The absorption seen by the SSS might be due to partially ionized, rather than neutral, oxygen. The estimation of excess column density of H I assumes that the primary absorber (oxygen) is in the neutral phase. The recent observations of A2256 with the Broad Band X-Ray Telescope (Miyaji et al. 1993) indicate that this is not always the case. Their observations indicate the existence of large amounts of ionized absorbing material at temperatures of 0.5–5 × 10^5 K. This gas is thought to originate by heating the cold gas through shocks or ionizing radiation. Although A2256 is not a cooling flow cluster the observations from BBXRT raise the possibility of such ionizing processes occurring in other clusters as well. If this is indeed happening it might explain the absence of neutral or molecular hydrogen in the cores of cooling flow clusters.

4.2. *The Detection of Cold Gas in Hydra A*

A continuum image of Hydra A made from the present observations is shown in Figure 2*c*. We detect H I absorption toward the core of Hydra A. The spectrum is shown in Figure 7. Note that the core has only a flux density of 372 mJy beam^{-1}. No absorption was detected toward any other direction in Hydra A although the flux density in several areas reaches up to 2 Jy beam^{-1}. Since the projected distance between the core and the inner lobes is about 10″ (~ 11 kpc), any absorbing cloud along the line of sight should be less than 11 kpc in size. In this case it would be by chance that we see absorbing material projected against the core and not against any of the more extended emission in Hydra A. Alternatively the absorbing material may be close (< 11 kpc) to the core itself.

There are several arguments why the latter possibility is more plausible. The core in Hydra A is unresolved at all VLA resolutions and has a flat radio spectrum (Taylor et al. 1990). Thus, by analogy with other such sources, it probably has a milliarcsecond size (e.g., Kellermann & Owen 1988). Along this line of sight the flux density in the synthesized beam is completely dominated by the core, much smaller than the resolution of $\sim 6''$. Thus the dilution effects, either spatial or in frequency will be less serious along this line of sight. To illustrate, if the absorbing cloud is spherical and has the same size as the core (1 pc, if the core is 1 milliarcsec) and is precisely in front of it, then, its H I mass could be as small as 4 $M_\odot$ to cause the observed absorption. At the other extreme, the upper limit of 10 kpc to the size of the cloud sets an upper limit to its H I mass of 4 × 10^8 $M_\odot$. The velocity structure makes it unlikely that we are picking up an ensemble of tiny clouds in front of the core. The properties of the H I absorption are very similar to those seen in two other cooling flow clusters 2A 0335+096, and MKW 3s (McNamara et al. 1990) and in more isolated radio galaxies (van Gorkom et al. 1989). For all these galaxies the absorbing systems are probably physically associated with the galaxy that contains the radio source. The absorption velocities are all within the velocity range spanned by the galaxy. Hydra A has a very complex kinematical structure, the velocities seen close to the center span a range of at least 750 km s^{-1} (Ekers & Simkin 1983) and the velocity of absorption line is well within the range. In Hydra A the absorption is seen only against the core, as is the case for the infalling clouds seen in absorption toward isolated radio galaxies (van Gorkom et al. 1989), suggesting that the absorbing material is physically close to the nucleus. The widths of the H I absorption lines seen toward isolated galaxies and the two cooling flow clusters are typically from a few tens to 150 km s^{-1}. The H I absorption in Hydra A with a line width ~ 50 km s^{-1} is similar to these. Speculations on the nature of these clouds have been made by McNamara et al. (1990) and van Gorkom et al. (1989), and our detection of a similar system towards one more source does not warrant a more elaborate discussion. However, it is remarkable that despite rather compelling evidence for the presence of large amounts of widely distributed cooling gas in clusters, cold gas (H I and H_2) has only been found in the centers of the cD galaxies in the cluster. The only feature that comes close to what is expected from the widely distributed gas is the very broad H I absorption feature seen against the core of Perseus A (Crane et al. 1982; Jaffe 1990).

4.3. *Where Is the Cold Gas*?

Even if the present SSS results turn out to be misleading there are many X-ray–imaging and spectroscopic results of clusters of galaxies indicating that in the centers of some clusters the densities of the X-ray–emitting gas are higher and the temperatures are lower than in the outskirts of the clusters. Based on these observations, the cooling flow models predict large amounts of intracluster gas condensing out of the flow on their way to (ultimately) low-mass star formation. If this is indeed the case, the present limits along with the nondetections of molecular gas in clusters imply that the amount of time the gas spends in neutral and molecular phases of hydrogen is less than 1%–10% of the time over which cooling flows exist. This is $\sim 10^8$–10^9 yr—relatively short compared to Galactic values. Alternatively, although there is some evidence for star formation in cooling flows, most of the gas may not be forming stars. In fact, the observations related to star formation in cooling flow clusters are not consistent with the mass inflow rates predicted from the X-ray data if the initial mass function resembles that in our Galaxy (O'Connell & McNamara 1988; Johnstone et al. 1987; Johnstone & Fabian 1989). The observations account for only $\sim 1\%$ of the cooling flow mass. The rest of the mass is thought to form low-mass ($< 1\ M_{\odot}$) stars (Fabian et al. 1991).

However, it is becoming increasingly clear that the existing cooling flow scenario is too simple and that reheating has to be taken into account. This would naturally explain the lack of H I and H_2. Recent BBXRT observations indicate that this is at least the case in A 2256 (Miyaji et al. 1993). Future high spatial and high spectral resolution X-ray observations are likely to clarify the situation.

5. SUMMARY

We have observed three clusters, Virgo, A2199, and A780, which are believed to be prime candidates for cooling flows. We detect a narrow (~ 50 km s^{-1}) absorption ($\tau \sim 0.07$) feature against the core of Hydra A (in A780). This narrow absorption might be related to the cooling flow gas or similar to the H I gas seen in many isolated galaxies. We also detect a spiral galaxy in A2199 with a total H I mass of $1.8 \times 10^9\ M_{\odot}$. Other than this no H I emission from such clouds were detected in any of the three clusters to a 3 σ upper limit of 10^7–$10^9\ M_{\odot}$. Apart from these isolated H I detections the present observations have not detected spatially extended neutral hydrogen gas as might be expected from cooling flows. We estimate a 3 σ H I column density limit of 5×10^{19} cm^{-2} for a spin temperature of 100 K and an assumed line width of 500 km s^{-1}. Our estimate of the total mass of H I ($< 10^{10}\ M_{\odot}$) within the cooling radius of 100 kpc is less than 1%–10% of the mass postulated by the cooling flow models ($\sim 10^{11}$–$10^{12}\ M_{\odot}$). We do not think such large amounts of H I could have escaped these absorption measurements. It is possible to reconcile the present limits on the column density of H I with that expected from the SSS observations by increasing the spin temperature of H I. However, such a gas would be optically thin and should be detectable in emission. The most sensitive search for H I emission from cooling flow clusters sets upper limits to the total amount of H I which are two orders of magnitude below what is expected. Our observations along with earlier H I emission measurements make it difficult to hide the H I predicted by the cooling flow scenarios.

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Note added in proof.—See Braine & Wiklind (A&A, 267, L47 [1993]) and Braine & Dupraz (A&A, 283, 407 [1994]) for more recent sensitive upper limits (10^7–$7 \times 10^8\ M_\odot$) on the molecular gas content in Virgo, A2199, and A780 clusters.