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DISCOVERY OF A LARGE INTERGALACTIC H I CLOUD IN THE M96 GROUP

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ABSTRACT

We report the discovery of an intergalactic H I cloud, found in the western part of the Leo group of galaxies, using the Arecibo 21 cm system. The cloud has a systemic radial velocity of about 960 km s^{-1}. The emission is found mainly in a region approximately 100 kpc long by 30 kpc wide midway between M96 and M105. Fainter emission, extending north and south of the cloud, spans about 200 kpc and reaches the vicinity of M96. The nominal H I mass of the whole cloud is about 10^9 $M_\odot$. However, because of the low rate of collisional excitation, $M_{\rm H\ I}$ may be substantially underestimated for this cloud—and for other H I clouds of very large extent and low density. The velocity structure of the cloud gives an indicative gravitational mass of at least 2×10^{10} $M_\odot$.

Subject heading: intergalactic medium — radiative transfer — radio sources: 21 cm radiation

I. INTRODUCTION

The serendipitous discovery of a large intergalactic cloud of neutral hydrogen was made in 1983 January at Arecibo Observatory[3] in the course of 21 cm line observations of groups of galaxies. The gas cloud is in the Leo complex of galaxy groups near M96.

Searches with good sensitivity in groups of galaxies (Shostak 1977; Lo and Sargent 1979; Materne, Huchtmeier, and Hulsbosch 1979) have shown that isolated intergalactic gas clouds are rare. Clouds which might have been in the Sculptor group (Mathewson, Cleary, and Murray 1975) were subsequently shown to be part of the Magellanic Stream (Haynes and Roberts 1979). In the general field, Fisher and Tully (1981) give an upper limit of less than 0.03 $\rm Mpc^{-3}$ for the density of isolated clouds with an H I mass greater than 10^8 $M_\odot$. A few individual galaxies show gas extending to many Holmberg radii in rough kinematic continuation of the disk (Fisher and Tully 1976; Briggs *et al.* 1980; Hart, Davies, and Johnson 1980; Appleton, Davies, and Stephenson 1981; Heckman *et al.* 1982; Huchtmeier and Richter 1982, and references therein), with "clumps" probably representing the outermost parts of the galaxy's warped and tilted disk, rather than a separate cloud (Sancisi 1981; Briggs 1982). In small groups, extended H I streams, plumes, and bridges are fairly common (Weliachew, Sancisi, and Guélin 1978; Haynes, Giovanelli, and Roberts 1979; Haynes 1981, and references therein), but separated clouds are not.

The gas cloud reported here is comparable in size to the largest appendages reported in the literature, but is distinct from the class of simple tidal streams and extended disks. The main body of the cloud, containing over 75% of the emission, is well isolated from the surrounding galaxies. The integrated H I flux of the cloud approximately equals or exceeds that of any of the neighboring galaxies and is concentrated more distantly from any galactic disk than previously reported features.

II. 21 CENTIMETER DATA

The discovery was made by one of us (S.E.S.) during an unsuccessful search for the redshift of UGC 5808. The observations were being carried out in the total power mode, and the "off source" position lay by chance at the edge of the cloud. After this first detection, the region was mapped at Arecibo at 21 cm, using the dual-circular feed, frequency switching in a total bandpass 2.5 MHz wide; the autocorrelator implemented three-level sampling at double the Nyquist rate. Over 120 points were observed for 3 minutes each on a grid with a spacing of 3′.8, the distance from the center to the first null of the beam. An H I map is given in Figure 1.

Second-order baselines were removed from all spectra; the maximum deviation of the baselines from a linear fit never exceeded 15 mJy. The spectra were Hanning smoothed once to give a final velocity resolution of about 4 km s^{-1} with noise levels of typically 5 mJy rms. Representative spectra from across the cloud

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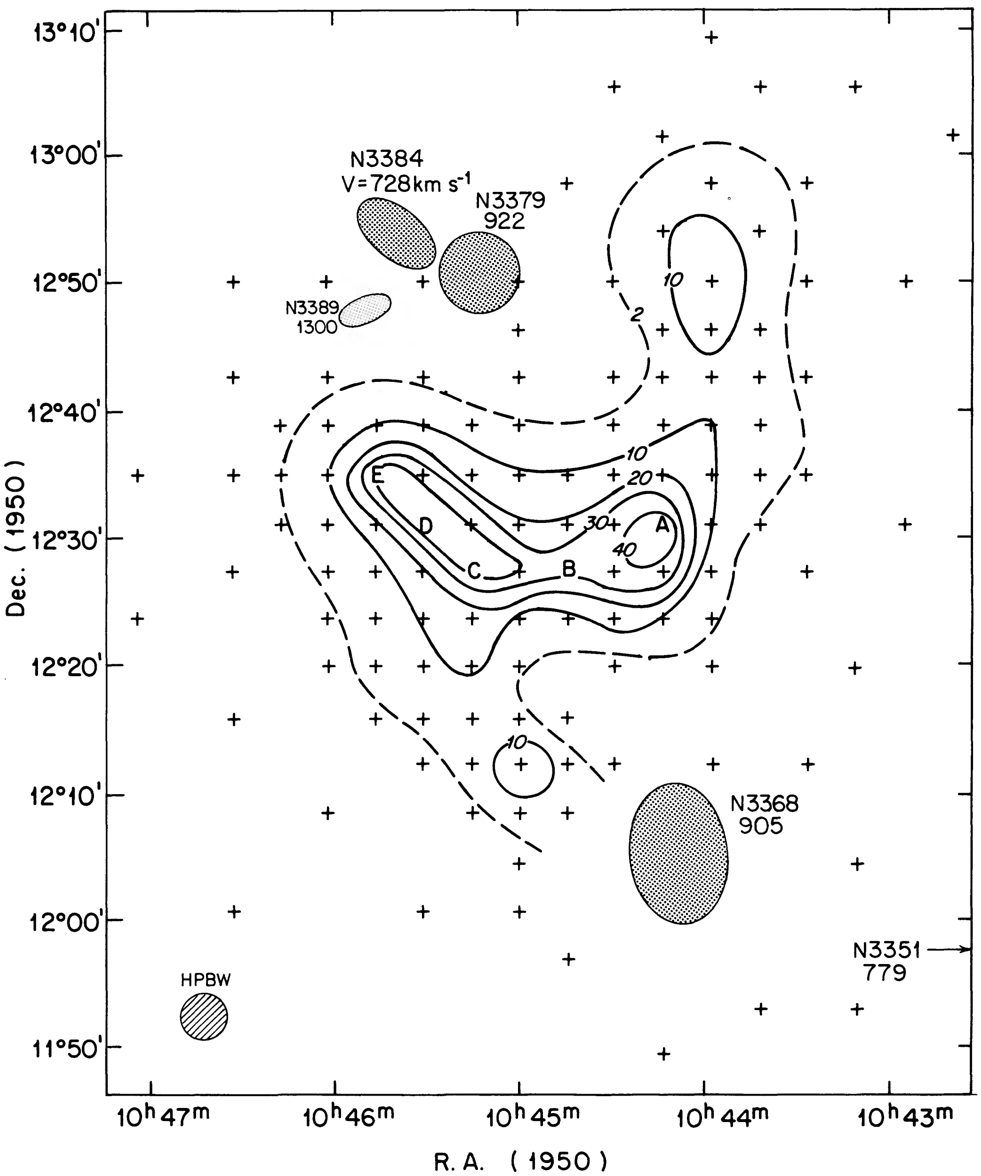

FIG. 1.—Neutral hydrogen map of the intergalactic cloud in the region of M96 (NGC 3368) in Leo. The plus symbols indicate the locations where H I spectra were obtained. Contours are drawn in units of K km s^{-1}. The positions and Holmberg dimensions of several Leo galaxies are indicated together with their heliocentric velocities.

are shown in Figure 2. The emission was spot-checked using the flat feed, which has better sidelobe characteristics, and no significant discrepancies were found.

The line fluxes were reduced to brightness temperatures, assuming a beam efficiency of 0.65, which includes an estimate of the first sidelobe contribution, and a forward gain of 8 K Jy^{-1}. Figure 1 shows a contour map of the integrated brightness temperatures drawn without any attempt at deconvolution. Integrating inside the smoothed brightness temperature contours, we find a nominal total H I mass for the cloud of $M_{\rm H\,I} = 1.6 \times 10^9$ $M_\odot$ D_{10}^2, where D_{10} is the distance in units of 10 Mpc.

The heliocentric redshift varies along the cloud from approximately 1050 km s^{-1} at the west edge to about 870 km s^{-1} at the east. The appendage to the south of the cloud has a mean velocity of approximately 970 km s^{-1}, close to the systemic velocity of the whole cloud, $V_{\rm cl}$ = 960 km s^{-1}. The velocity width (FWHM) of individual emission profiles varies from 25 to 60 km s^{-1}.

III. DISTANCE, SIZE, AND MASS

The Leo region of galaxies, 15° in diameter with velocities from approximately 600 to 1400 km s^{-1},

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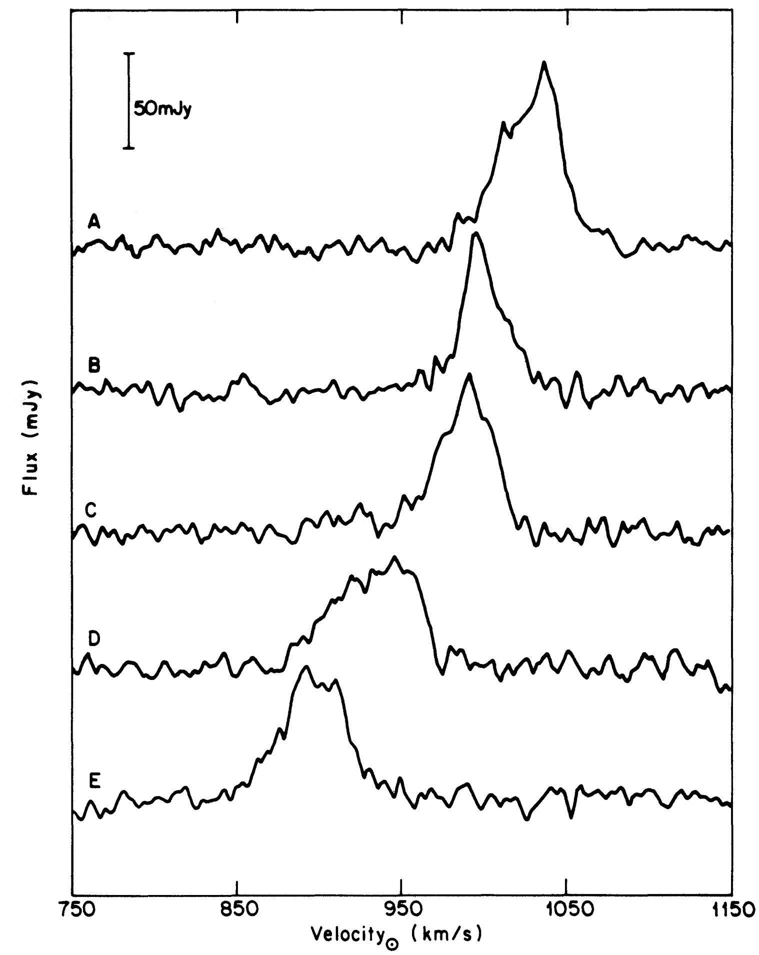

FIG. 2.—Five H I spectra (A to E) across the Leo intergalactic cloud at the corresponding positions indicated in Fig. 1. In units of brightness temperature, 50 mJy ~ 0.6 K.

consists of three to five fairly compact subgroups. Three of the galaxies in the rectangle in Figure 1, NGC 3368 (M96), NGC 3379 (M105), and NGC 3384, along with NGC 3351 (M95) just outside to the west, are part of the nearest, western subgroup (G11 or GWa), which has more members (NGC 3377, NGC 3412, and NGC 3489) farther north and east (Materne 1978; de Vaucouleurs *et al.* 1981). The subgroup GWa consists of early-type galaxies, except for the spirals M95 and M96, and has a mean (heliocentric) redshift of approximately 810 km s^{-1}. Another bright galaxy in Figure 1, NGC 3389, belongs to the subgroup GWb which has a mean redshift of approximately 1300 km s^{-1}. Independent distance estimates (de Vaucouleurs *et al.* 1981) put the nearer subgroup GWa at a distance of about 10 Mpc and NGC 3389 at least 1.5 times farther away. The systemic velocity of the cloud is 960 km s^{-1}, close enough to the mean of GWa that it could be located right in the middle of this subgroup.

At 10 Mpc, the cloud radius of approximately 15′ corresponds to $R \sim 50$ kpc. In the emission peaks, the column density nominally reaches about 7×10^{19} H cm^{-2}. If the depth of the cloud along the line of sight is 50 kpc, the maximum H I density near these points is approximately 4×10^{-4} H cm^{-3}, but closer to 10^{-3} H cm^{-3} if the cloud is more nearly "finger-like." This is still at least 100 times below interstellar medium densities, and the lack of normal star formation should be no surprise.

The main body of the gas cloud is well isolated and has a steep falloff in column density from the ridge of peak intensity. If the cloud had no internal gravitational force, and if the observed velocity gradient of approximately 160 km s^{-1} per 100 kpc were indicative of a dispersal velocity, the cloud would double in size in less than 10^9 years, and the sharp boundaries would be washed out even more rapidly. If the cloud were orbiting around a massive galaxy, the differential rotation

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would give a somewhat slower dispersal, but still fast compared with a Hubble time. The simplest hypothesis is that a substantial gravitational mass, M_{gr}, resides inside the volume of the cloud and that it is in approximate virial equilibrium.

The value of M_{gr} depends somewhat on the model. If the set of profiles in Figure 2 is interpreted as a single rotation curve with the (warped) plane extending from position A to E, the maximum rotation velocity is $V_{rot} = 80$ km s^{-1}, with a rotation period of 4×10^9 yr. For an edge-on disk with the gravitational mass distributed spherically, $M_{gr} \sim 1 \times 10^{11}\ M_\odot$; for an inclination of 60° to edge-on, M_{gr} could be 3 times larger. Since the velocity distribution of the gas is bimodal in character, one might instead model the gas cloud as two independently virialized components. The gravitational mass could then be as small as $2 \times 10^{10}\ M_\odot$, if it were as concentrated as the gas.

The total indicative mass of the four nearby galaxies of this subgroup is approximately $6 \times 10^{11}\ M_\odot$. The masses of NGC 3351 and NGC 3368 are 1.0 and $2.1 \times 10^{11}\ M_\odot$ respectively (Dickel and Rood 1978). The masses of NGC 3379 and NGC 3384 are 1.6 and $0.9 \times 10^{11}\ M_\odot$, respectively, if we assume a ratio of $M/L = 10$ (Faber and Gallagher 1979). The nominal mass of the gas cloud is, in any case, substantially smaller than the total mass of the system and does not in itself represent enough hidden mass to bind the group.

The nominal H I mass we derived in § II for the cloud was only about $10^9\ M_\odot$; however, an upward correction factor for column density $N_{\rm H\,I}$, and hence for $M_{\rm H\,I}$, may be important for this cloud as well as for other large gas halos and plumes of low volume density $n_{\rm H\,I}$. In such cases, the ratio α of the collisional to the radiative de-excitation rates of the upper hyperfine level in H I is

$$\alpha \approx \frac{n_{\rm H\,I}}{5 \times 10^{-3}\ {\rm cm}^{-3}} \left(\frac{T_{\rm gas}}{10^3\ {\rm K}} \right)^{0.6} \qquad (1)$$

according to Spitzer (1978). When $\alpha \ll 1$, the observed line flux (in excess of the microwave radiation background) is given by the collisional excitation rate of the upper level. For small optical depth, the ratio of true H I column density to observed line flux is larger than that given by the standard formula by a factor α^{-1}. Of course, the gas kinetic temperature, $T_{\rm gas}$, of an intergalactic cloud is uncertain and $n_{\rm H\,I}$ depends on the cloud geometry, but we would estimate that the factor is between 5 and 20 (with similar factors for tenuous halos and plumes). The actual value of $M_{\rm H\,I}$ for the cloud is probably of the order of $10^{10}\ M_\odot$, still less than our most likely estimate for the virial mass M_{gr}, but not by a very large factor.

IV. SUMMARY AND DISCUSSION

We have detected a neutral gas cloud in the M96 group of galaxies of radius $R \sim 50$ kpc and nominal hydrogen mass $M_{\rm H\,I} \sim 10^9\ M_\odot$, assuming a distance of 10 Mpc. The cloud is concentrated away from the neighboring galaxies, which do not show signs of optical distortion. Compared to tidal features found in some galaxy groups, the gas cloud is at least quantitatively more extreme: (*a*) the spatial extent of the cloud is larger; (*b*) the individual spectra show greater velocity widths; and most importantly, (*c*) the H I mass situated more than 3 Holmberg radii away from any individual galaxy center is much larger both in percentage and absolute amount for this cloud. The extreme tidal feature in the literature, the H I stream in the Leo triplet (Haynes, Giovanelli, and Roberts 1979), has only 5% ($\sim 10^8\ M_\odot$) as much gas exterior as interior to 3 Holmberg radii, while for this cloud there is 100% as much gas involving more than $10^9\ M_\odot$. A few unusual H I disks about early-type galaxies have large quantities of gas extending to many Holmberg radii (Hawarden 1982), but otherwise they have little in common with this cloud.

The gas cloud presents an opportunity for exploring the gravitational mass distribution of a group away from individual galaxies. The simplest hypothesis for containment of the cloud is by approximate virial equilibrium provided by a gravitational mass, M_{gr}, internal to the cloud. This requires an M_{gr} of the order of $10^{11}\ M_\odot$ which is probably (but not certainly) more than can be provided by the mass of gas itself. The virial equilibrium for the GWa group of galaxies (and all other groups and clusters) in any case requires much more unseen matter than $10^{11}\ M_\odot$.

Although it is unclear how the gas cloud originated, we suggest three possibilities for further observations. First, the cloud is in a "clean region" in the Leo group, containing several bright galaxies but a dearth of fainter ones. If intergalactic gas clouds are easily dispersed or accreted by collisions with galaxies, then searches in other "clean" galaxy groups might reveal more clouds. Second, the distinction between a "true intergalactic gas cloud" and a galaxy with large radius and small surface density depends on the mass-to-light ratio. No optical emission is discernible on POSS plates, which have a detection threshold of approximately 25 mag arcsec^{-2} (de Vaucouleurs, de Vaucouleurs, and Corwin 1976), so that we can already eliminate a galaxy with a normal or low M/L ratio. Skrutskie, Shure, and Beckwith (1983) have set limits at least 2 mag fainter at points in the cloud's density peaks, so that even for a high value of $M_{gr}/L = 20$, stellar emission would most likely have been detected already. However, any signs of star formation or old stars would be of interest even if M/L is

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quite large. Third, an alternative mechanism for inhibiting the cloud's dispersal would be its immersion in a much larger ionized cloud of "coronal gas" at about 10^6 K in pressure equilibrium. A search for soft X-ray emission in the region surrounding the cloud would be useful.

Finally, we raise a point of radiative transfer theory which is of potential importance for the intergalactic gas cloud and all other extended H I regions where a very long pathlength means that very low values of volume density $n_{\mathrm{H\,I}}$ may still be observable. The possibility exists that the H I mass and the spatial extent have been underestimated for H I regions studied in emission. The outermost envelopes, weak in emission but strong in absorption, might provide an explanation for the long-standing puzzle of the many low-redshift absorption systems found in quasar spectra.

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